MONTROSE COASTAL CHANGE ASSESSMENT

2024 survey report & risk assessment update

Craig MacDonell, Martin Hurst, Alistair Rennie, Larissa Naylor, Lyle Keith & Croy Langlands

dynamic.coast@nature.scot | coastaladaptation@glasgow.ac.uk

Published: 13th May April 2025

University of Glasgow | School of Geographical & Earth Sciences

Dynamic Coast

1 Executive Summary

Angus Council have commissioned the University of Glasgow to work with Dynamic Coast to undertake an update on the coastal erosion effecting Montrose beach and links and consider the implications on flood and erosion risk management in our changing climate. The researchers compiled all available data since the Dynamic Coast's 2021 publication and undertook additional surveys in September and October 2024 (for Montrose and St Cyrus, respectively). This updated dataset was analysed and projected forward to 2300 to predict future changes to the dune system and the consequential implications of continued dune erosion for the flood protection that the dunes currently provide.

The key findings are:

1. Erosion continues to affect much of the dunes and many parts of the beach within Montrose Bay, with some of the fastest known rates of change on record measured during winter 2023/24. Up to 12 m of dunes have been lost over a few stormy days coinciding with spring tides.
2. The observations also provide complex and mixed messages which require further monitoring. The dunes have changed more rapidly, meaning that risks of widescale dune breaching are likely to happen sooner than previously thought (within a few decades). However, parts of the upper beach have been temporarily fed by these dune losses, abating beach losses, which paradoxically pushes these risks further away into the future (after 2100). Only time and more frequent monitoring will reveal which pathway we are on; and which of a range of adaptation actions we were right to plan for.
3. Adaptation planning often has uncertainties like this, which are best managed through an adaptive pathways approach. The recent changes underscore the importance of the three-fold dynamic adaptive approach published in 2021 and adopted by the council, and suggests there is little time to waste in actioning all three of these to keep communities and assets safe:
   (1) implement short term adaptations to address present flood risk,
   (2) address the causes of erosion through measures to replenish and retain beach face sediment, buying time to
   (3) develop and action a range of wider adaptation plans and actions across the peninsula.

The following recommendations are made:

1. The recent survey and analysis confirm that Angus Council is justified in its continued efforts to understand the underlying causes of the erosion, and to use short term adaptation measures (including but not limited to sandbag structures) which will buy time for the community, local authority and wider stakeholders to develop and start to action longer-term adaptation strategies. These should be in support of requirements to develop and implement a Coastal Change Adaptation Plan (CCAP) and report progress on adaptation under the Climate Change (Scotland) Act 2010.
2. Given the continued rate of coastal change and its complexity, a monitoring strategy is essential to continue to inform operational discussions alongside adaptation options. A proposed cost-effective and proportionate monitoring strategy is outlined within the report.

Please note there is a Glossary of key terms and acronyms at the end of the report.

2 Introduction

2.1 Purpose of this document

This report provides a review of recent coastal changes across Montrose Bay (Angus, Scotland), and updated perspective on future coastal changes, undertaken by the University of Glasgow (UoG) and Dynamic Coast, in partnership with Angus Council. The results supersede the Dynamic Coast (2021) analysis and better informs recent and anticipated future coastal changes under a range of climate scenarios. Whilst the analysis extends from the River South Esk (in the south) to the tip of the dunes at St Cyrus (in the north), additional attention is directed to the dunes within the southern part of the golf course. These dunes provide natural flood protection but are subject to rapid coastal erosion and are of particular interest to Angus Council.

2.2 Structure of this document

In the following sections we report on the four key tasks outlined in the Statement of Requirement:

1. Compile the available evidence base on coastal change at Montrose Links (and adjacent shore) with relevance to coastal erosion, flooding and erosion-enhanced flood risk. Undertake additional summer survey(s) to update key areas and be reflexive to storms for further response survey.
2. Analyse changes within this evidence base, including variability/uncertainty to inform a detailed picture of recent changes, considering both long-term trajectory and the impacts of individual storms or storm clusters.
3. Use observed changes and their variability, alongside future sea level rise scenarios (tied to global greenhouse gas emissions/shared socioeconomic pathway scenarios), to inform an assessment of the relative flood protection value offered by the dunes, under a do-nothing coastal management strategy.
4. Develop a cost-effective coastal monitoring strategy for Angus Council to inform their local decision making.

2.3 Context

Rising sea levels caused by climate change are expected to increase Montrose's coastal erosion and flood risk during this century (Figure 1). The extent of this increase is uncertain and will depend upon global efforts to control increasing atmospheric temperature due to carbon greenhouse gas emissions Globally, the average rate of eustatic sea level rise (due to melting terrestrial ice, and thermal expansion of the oceans) is currently 3.5 mm/yr. Even in the best-case scenario (achieving global net-zero emissions immediately), sea level rise will continue for decades to come (MetOffice, 2024). However, our current trajectory is tracking a high emissions scenario (Schwalm et al., 2020).

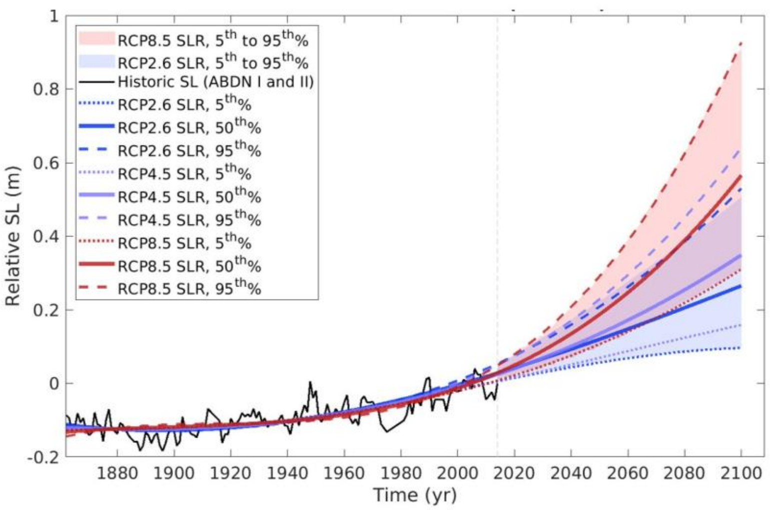


Figure 1a: UKCP18 Future Sea Level for Aberdeen (as a proxy for Montrose) under various scenarios for future greenhouse gas emissions. Solid lines show the most likely trajectory for each scenario while the shaded regions show the 90% confidence interval. These projections are based on the Met Office's UK Climate Projections (UKCP18; (Met Office, 2019)).

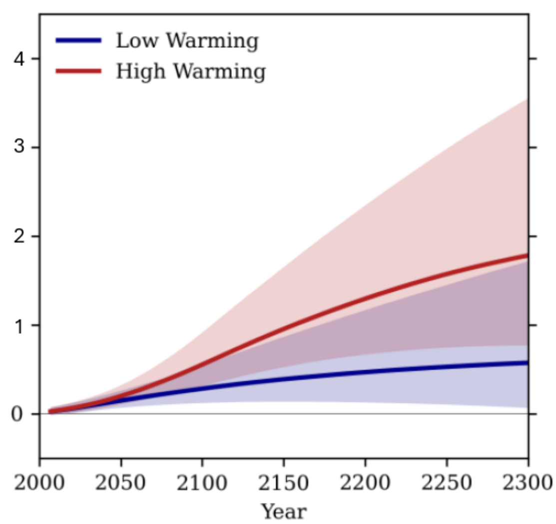


Figure 1b UKCP18 Future Sea Level for Aberdeen (as a proxy for Montrose) under various scenarios for future greenhouse gas emissions, extended to 2300. (Palmer/MetOffice, 2024).

Dynamic Coast has provided the best available means of understanding the potential for coastal erosion and erosion-enhanced flooding on a national and regional scale in Scotland. University of Glasgow and Dynamic Coast are working with Angus Council to better understand coastal change at Montrose in order to provide updated evidence to support the council's flood risk management obligations and plans, but this research also informs wider coastal change adaptation duties the council also has in support of statutory planning and climate change duties.

Angus Council's approach to coastal management is set out in their (2017) Shoreline Management Plan 2 (link). The specific policies for each of the Management Units (MU) are summarised below (link, see p4):

- MU1/1 north of golf course: Short, Medium and Long-term: Non-Active Intervention.
- MU1/2 golf course: Short, Medium and Long-term: Managed Realignment.
- MU1/3a Splash: Short and Medium-term: Hold the line. Long-term: Managed Realignment.
- MU1/3b Holiday Park: Short and Medium-term: Hold the line. Long-term: Managed Realignment.
- MU1/4 Glaxo: Short, Medium and Long-term: Hold the line.

Angus Council have published further context on their Montrose Coastal Erosion webpage.

It is hoped that this report, and any further research is of value to partners across Montrose Bay. In this regard, the efforts of Montrose Links Limited are noted, as they continue to invest in the links courses within and behind the dunes. The club has undertaken adaptation planning over the years and is continuing to take adaptive measures to ensure golf continues to be played. Realignment of pars of the 2nd and 3rd tees is underway (May 2025).

3 Location Context

Throughout this report, several locations will be referred to, including geographical locations, but also locations relative to the 1568 golf course (main course) on the Montrose Golf Links, as detailed in Figure 2.

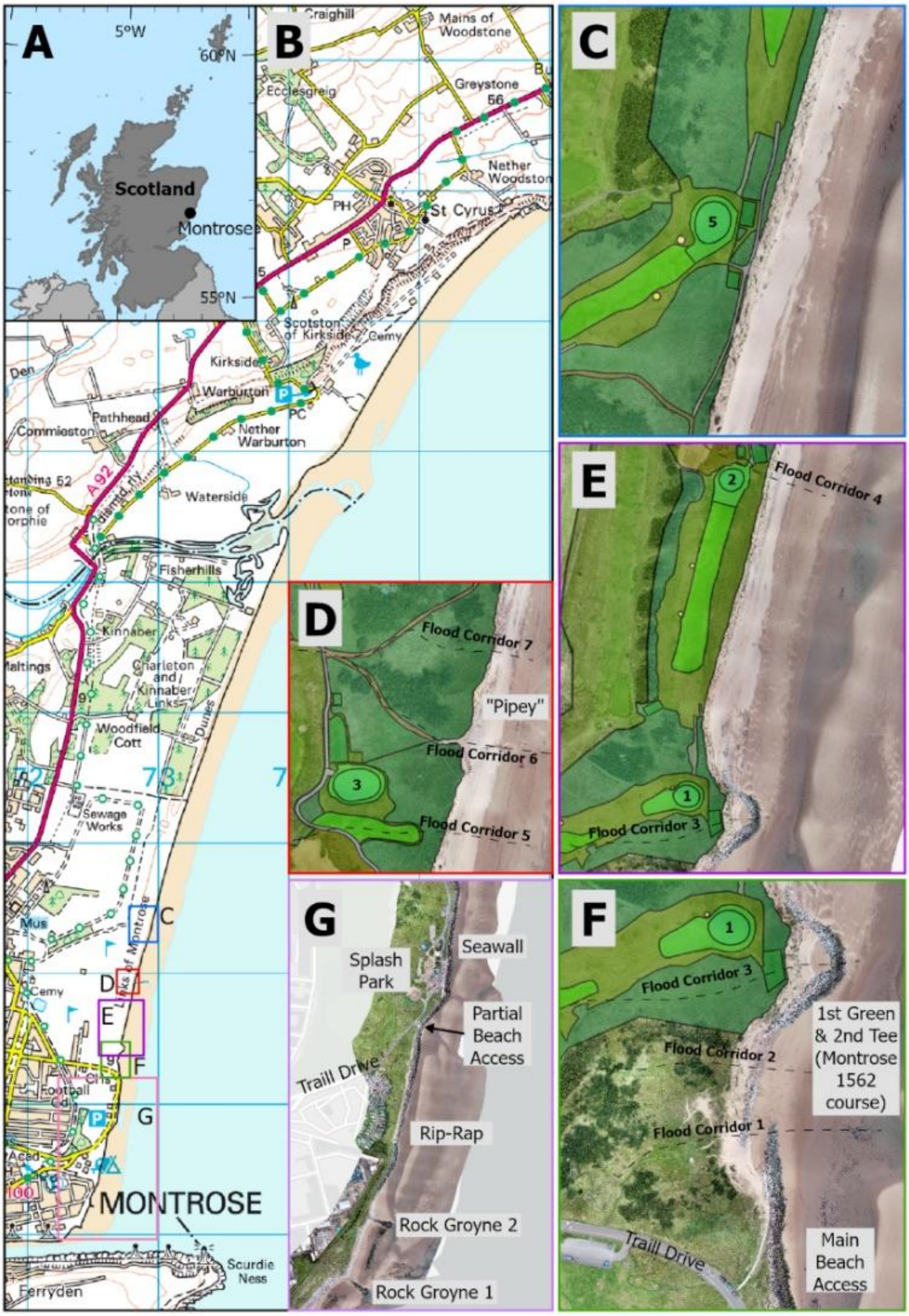


Figure 2: Map of relevant locations along Montrose Bay, notably coastal defence structures, hole locations on Montrose Golf Links (1562 course) and identified flood corridors. Ordnance Survey 1:25,000 scale topographic map and GB Light Grey Basemap, © Crown copyright and database rights 2025 Ordnance Survey (AC0000851941). Country outlines: GADM. © Bluesky International Ltd. & Getmapping Plc. (2025).

4 Task 1: Survey datasets

Task 1 was to compile the available evidence base on coastal change at Montrose Links (and adjacent shore) with relevance to coastal erosion, flooding and erosion-enhanced flood risk, including undertaking an additional post-summer survey to update key areas, and to be reflexive to storms for a further response survey. Whilst Montrose Links were the primary focus of the work, NatureScot provided additional funding to extend the survey into St Cyrus. The following datasets were used to update our understanding of coastal change, following the Dynamic Coast Montrose Super Site report (published 2021).

Table 1: Additional survey datasets which have been used to update analysis of coastal change at Montrose, including estimated horizontal and vertical accuracy.

Date	Original Product Source & Method	Extent	Products	Est. Accuracy
2018-08	OS Smarter MHWS		MHWS	± 0.2m
2018-04	OS Aerial / LiDAR	South Esk to North Esk & St Cyrus	MHWS / DEM	± 0.2m
2013-06-14	University of Glasgow – DEM interpolated from GPS points collected on foot and quad bike **– used in Montrose/St Cyrus Supersite report only**	Traill Drive to North Esk & St Cyrus	MHWS / DEM	± 0.5m
1964 – 1982 (1970s)	DC2 1970s MHWS – Ordnance Survey maps (1:10,000)	South Esk to North Esk & St Cyrus	MHWS	± 1m
1901 – 1904 (1890s)	DC2 1890s MHWS – Ordnance Survey maps (Six inch to mile, 1:10,560)	South Esk to North Esk & ~ northern $^{1}/_{4}$ of St Cyrus	MHWS	± 5m
2025, 2020 & 2010	Mean Low Water Springs – Ordnance Survey (OS MasterMap)	Montrose Bay	MLWS	±2.5m
Datasets not used in DC2				
Date	**Original Product Source & Method**	**Extent**	**Products**	**Est. Accuracy**
1957	Ordnance Survey map	South Esk to North Esk & St Cyrus	MHWS	± 2m
2006-09-08	Aerial Photography Great Britain (APGB) Aerial Photogrammetry	South Esk to North Esk & St Cyrus	MHWS / DEM	± 0.5m
2011-04-30	Digimap	National	Ortho	-
2013-05-25	Digimap	National	Ortho	-
2015-10-01	APGB / BlueSky GetMapping	South Esk to North Esk & ~ southern $^{2}/_{3}$ of St Cyrus	MHWS / DEM	± 0.5m
2016-06-01	APGB / BlueSky GetMapping	Northern $^{1}/_{3}$ of St Cyrus	MHWS / DEM	± 0.5m
2018-07	UoG Quad Bike GNSS	Montrose – 2018-07-30 St Cyrus – 2018-07-31		± 0.5m
2020-01 / 04	Montrose Port Authority (MPA) – UAV & EchoSounder	South Esk to North Esk	MHWS / DEM	± 0.2m
2023-04-21	BlueSky 2m	National		± 0.5m
2023-06-07	Montrose Golf Links – UAV Photogrammetry	~160m south of south seawall access to front of 7th green	MHWS / DEM	± 0.2m
2023-11-24	DynamicCoast / NatureScot – UAV Photogrammetry	Traill Drive to approx. halfway along 4th hole	MHWS / DEM	± 0.2m
2024-03-18	Angus Council commissioned SkyKam – UAV Photogrammetry	Traill Drive to approx. front of 4th green	MHWS / DEM	± 0.1m
2024-09-05	Glasgow University UAV LiDAR (Montrose)	South Esk to North Esk	MHWS / DEM	± 0.2m
2024-10	Glasgow University UAV LiDAR (St Cyrus)	Beach & Nature Reserve	MHWS / DEM	± 0.2m

5 Task 2: Historic Coastal Change Assessment

Task 2 aims to analyse coastal changes within the evidence base (Task 1), including variability/uncertainty to inform a detailed picture of recent changes, considering both long-term trajectory and the impacts of individual storms or storm clusters. This includes detailed change assessment of the upper beach, which can provide protection during storms, alongside change assessment of the lower beach and wider changes elsewhere. The analysis is used in Task 3 to inform future coastal change.

Several independent approaches have been used to investigate historic coastal change. The coastal indicators used are the spatial position of:

i. Mean High Water Springs (MHWS),
ii. Mean Low Water Springs (MLWS) and
iii. the seaward edge of coastal vegetation (VE).

Volumetric changes have also been calculated between the dates of the three-dimensional (3D) topographic surveys. Such a mixed method approach serves to cross-validate and provide confidence to inform assessment of the trajectory of coastal change at Montrose, while also providing insights into linkages and feedbacks between different parts of the coastal system.

5.1 MHWS from LiDAR & topographic surveys

5.1.1 Data and Methods Statement

Assessment of shoreline change in the 2021 Dynamic Coast 2 project was based on available mapped positions of MHWS at that time, the most recent of which was dated August 2018. Viewing Table 1 six additional data products have been collected since this time and were available for the analyses conducted herein. It must however be noted that the extent of all these surveys vary, with the extents being detailed on Table 1 also.

For the assessment of shoreline change in the 2021 Dynamic Coast 2 project, rates of change were calculated based on the difference between the most recent mapped position of MHWS (which was then in 2018), and a previous MHWS position that was at least four years older [Hurst et al., 2021]. This was to ensure that change was being analysed over a period of time long enough to not be substantially biased by any recent seasonal or storm-related variability. With the increase in frequency of coastal surveys at Montrose, particularly in 2023 and 2024, the approach to calculating rates of change has been modified to reflect the richer timeseries of survey data. We now perform a time-weighted linear regression on shoreline positions through time, with the shoreline position of more recent (and likely more accurate) surveys being of relatively greater importance to the calculation of the regression. Such an approach ensures that all available datasets were incorporated within the analysis, but also that any recent, short-term variations do not dominate the signal of change. A characteristic timescale controls the reduction in weighting with time back into the past, according to a decay function (i.e. older datasets are less important to the calculation of rates of change). An example of the normalised weightings from the first transect at Montrose (North Esk) is shown in Table 2. Noting that there is a trade-off between this characteristic timescale, and the resultant rates of change calculated, a decay timescale of 10 years was used to calculate the updated coastal change rates (Figure 3).

*Table 2: Weighting applied to shoreline positions for Transect 373 (near the 3e tee) using the new weighted regression method for calculating historic shoreline change rates. *NB where the actual date is unknown, 1st of the month or 1st Jan. is assumed.*

Shoreline Date	Weighting Factor (%)		Shoreline Date	Weighting Factor (%)
1901-01-01*	0.00006%		2018-01-01*	8.07%
1957-01-01*	0.018%		2018-04-01*	8.28%
1982-01-01*	0.22%		2020-02-28	10.01%
2006-09-08	2.60%		2023-06-07	13.90%
2013-06-14	5.12%		2023-11-24	14.56%
2015-10-01*	6.44%		2024-03-18	15.02%
			2024-09-05	15.74%

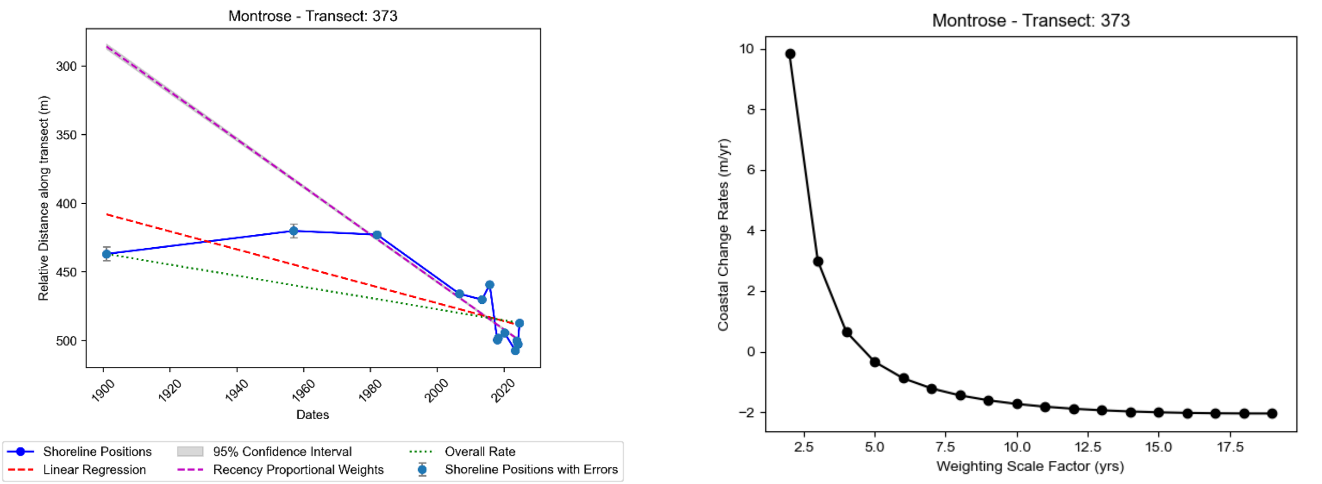


Figure 3: Example plots of the testing and evaluation of the updated time-weighted regression methodology; a) data points with uncertainties, and various regression metrics plotted, recency proportional weights (purple dashed with grey 95% CI area) is the option used in the new methodology; b) experimenting with how different time-weighting scale factors affect the final rate of change for a given transect, where the rate begins to become constant (> 10 years) shows where the method become less sensitive to individual shoreline positions. Note that due to recent accretion in 2024, a positive coastal change rate is derived when the scaling factor is small (<5 years), but with a scaling factor >10 years the longer-term trajectory of coastal retreat is borne out by negative coastal change rates indicating erosion.

5.1.2 Key Results

Figure 4 displays the changes published in 2021, on the left-hand side, compared with the updated changes following the 2024 survey of MHWS on the right-hand side. This comparison is made on a like-for-like basis, in that the changes observed up to 2024 are calculated based on the difference between 2024 survey and a previous survey that is at least four years older (2020 for Montrose or 2018 for St. Cyrus). Recent changes observed between the North and South Esk are generally dominated by upper beach erosion, particularly at Kinnaber Links and around Traill Drive defences. Adjacent to the golf course, the upper beach changes are more variable with an alternating pattern of erosion and accretion repeated in an alongshore direction towards the north. The median rate of change to MHWS over the four and a half years between 2024 and 2018 is -0.17 m/yr between the golf course frontage to the South Esk. It is noteworthy that MWHS has advanced across many natural sections of shore, however adjacent to hard defences (where dune erosion is largely curtailed) MHWS has not recovered seawards (e.g. the Carvan Park, Traill Drive/Splash and defences at the southern part of the golf courses) where the median rate of change is -0.28 m/yr (2024-2020). Likewise upper beach erosion is also occurring to the north of the walkway and to the north of the Pipey. The changes are spatially variable, most likely reflecting the presence and movement of sand bars on the upper beach (see volumetric analysis below). Within Kinnaber Links, the upper beach gains become more modest and switch to erosion towards the North Esk (median change -0.59m/yr, 2024-2020). Within the southern parts of St Cyrus, MHWS now sits seawards of the 2018 position, reoccupying the 2012 position in the south of the National Nature Reserve. The upper beach accretion continues for much of the central section of beach too, however the stability is observed within the norther third of St Cyrus. The median rate of change at St Cyrus is +3.42m/yr (2024-2018).

As explored within later sections of the report, we assert that the positive changes (gains) to parts of the upper beach (MHWS) are likely temporary, and linked to losses from the adjacent dunes, and such gains are largely absent from areas which are defended. Given the given the complex interaction between dune retreat and beach gains, and the increasing availability of data, the standard methodology developed in 2021, struggles to account for the complexity of these changes.

The weighted regression approach is less sensitive to bias due to recent storm impacts and therefore provides our current best estimate of coastal change rates for MHWS up to late 2024 (University of Glasgow UAV LiDAR surveys in September and October 2024) as can been seen in Figure 5.

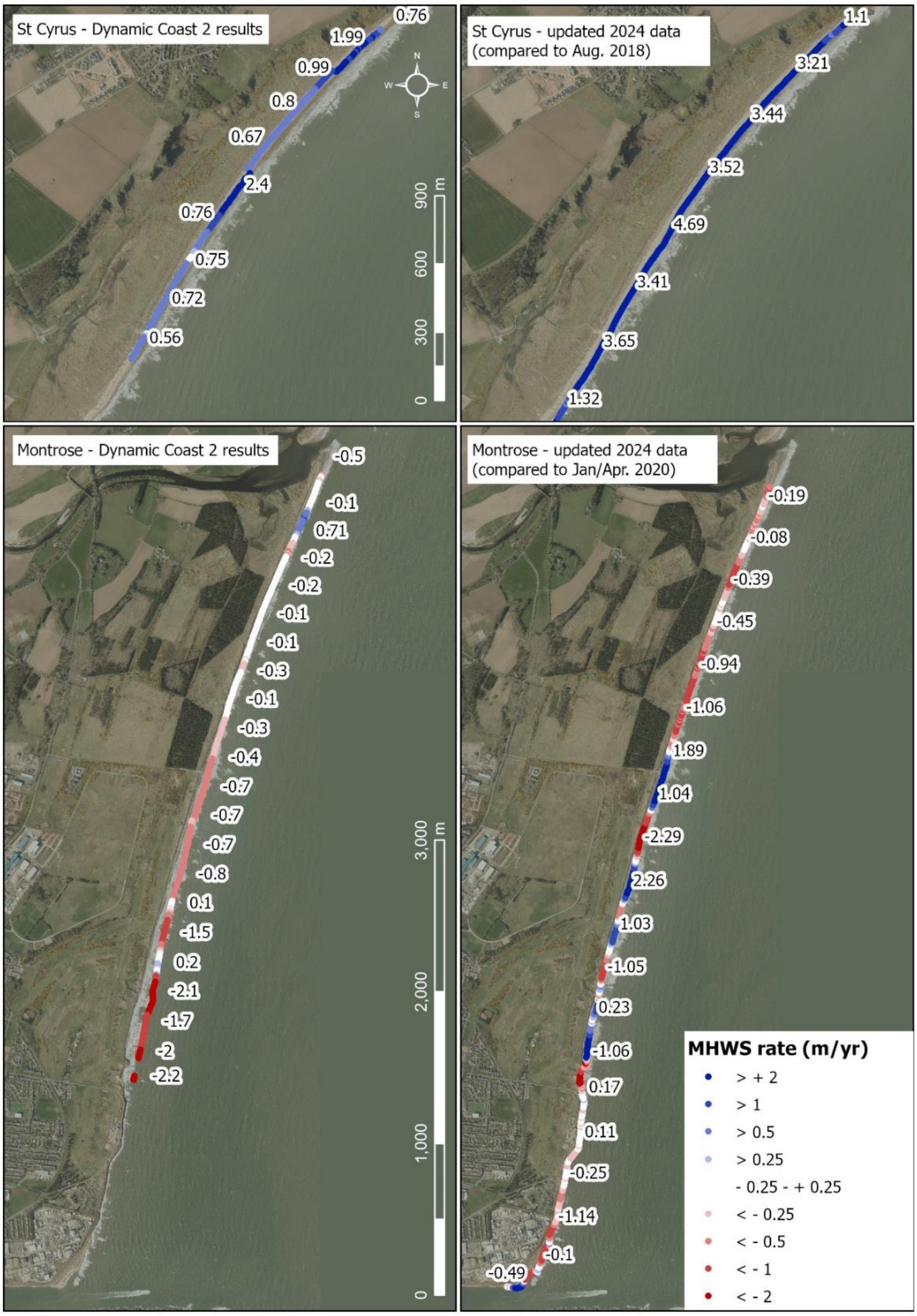


Figure 4: Maps showing rates of coastal change to MHWS at St Cyrus (top) and Montrose (bottom); on the left as published in Dynamic Coast (2021); and on the right showing our current best estimate of the rates of coastal change up to latest surveys in September/October 2024. Note, the two panels on the right of the map show a direct comparison between the most recent surveyed position and previous positions (August 2018 and Jan./Apr. 2020) that were more than 4 years previous (consistent with old Dynamic Coast methodology) and had full coverage of the respective beaches. © Crown copyright and database rights 2025 Ordnance Survey (AC0000851941). © Bluesky International Ltd. & Getmapping Plc. (2025).

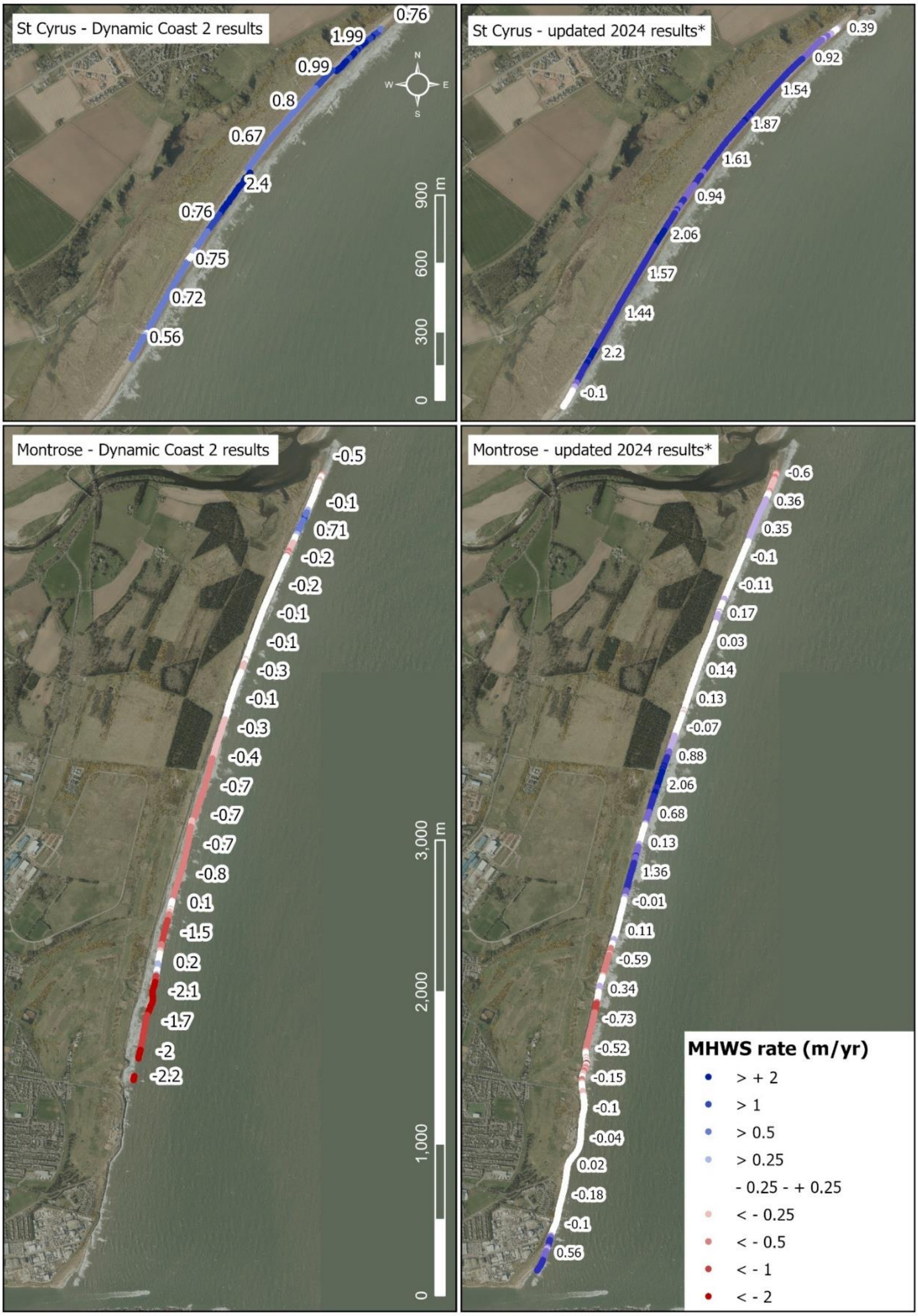


Figure 5: Maps showing rates of coastal change to MHWS at St Cyrus (top) and Montrose (bottom); on the left as published in Dynamic Coast (2021); and on the right showing our current best estimate of the rates of coastal change up to September/October 2024, calculated using the weighted regression approach. © Crown copyright and database rights 2025 Ordnance Survey (AC0000851941). © Bluesky International Ltd. & Getmapping Plc. (2025).

The updated annual MHWS change rates shown in Figure 5 exhibit continued, but moderated erosion along Montrose beach, stretching from the coastal defences near the main beach access at Traill Drive (see Figure 5), and northwards for approximately 1.2 km (3,000 m chainage - Figure 5). This moderation of the earlier erosion rates is attributed to the change in methodology (to weighted regression) providing a more robust trajectory of change that is less sensitive to biases associated with recent variability, and incorporates multiple recent datasets as outlined in Task 1.

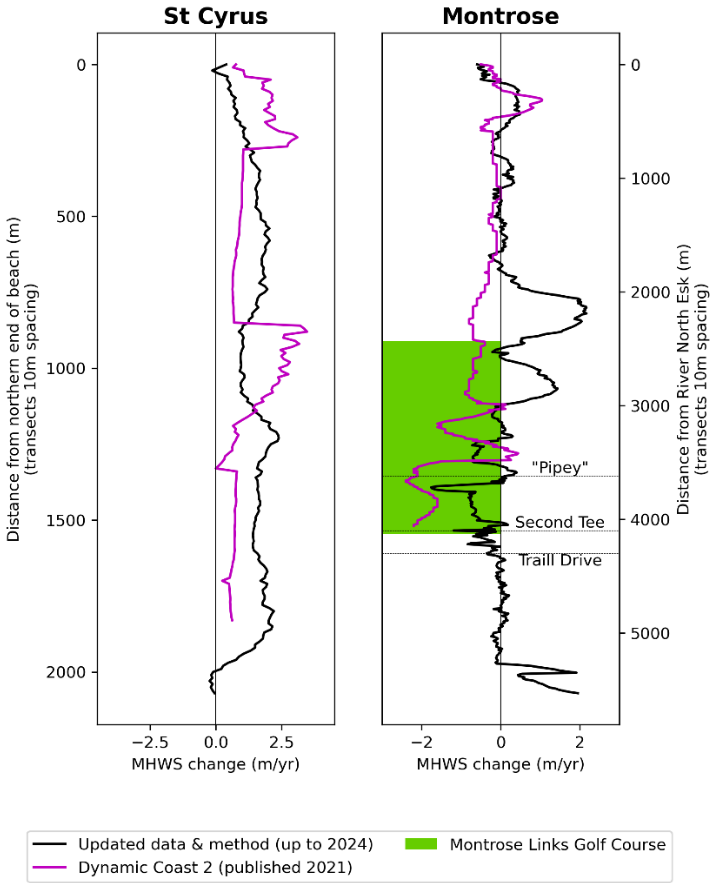


Figure 6: Plot showing changes to MHWS comparing the Dynamic Coast 2 rates in pink (as published in 2021) and the updated rates (additional data and revised weighted regression rate calculation method) in black.

5.1.3 Implications

Caution is urged in interpreting these changes to MHWS, these results do not suggest there has been any reduction in rates of change as such, but rather provide a more robust perspective on the long-term average informed by a richer array of data. Furthermore, changes to MHWS must be considered in the context of wider adjacent changes including Vegetation Edge and volumetric change analysis. There are also two notable patches of MHWS accretion identified (black line to right of centre line in Figure 6). The majority of the beach adjacent to Charleton & Kinnaber Links is showing a degree of stability with reference to MHWS position.

The implication of apparently more modest erosion across parts of the upper beach, is that anticipated future erosion is expected to be slower into the future than had previous been observed and predicted. It is important to emphasise that the recent apparent more modest changes to MHWS have been greatly influenced by large amounts of sediment being eroded and released from the adjacent dunes (see Vegetation Edge changes, below). Thus, some caution should be urged in the interpretation that the lower erosion rates tell the whole story. Continued monitoring of the foreshore is required to validate and update these rates as change continues.

MLWS from published OS mapping

5.1.4 Data and Methods Statement

The September 2024 LiDAR survey was conducted at low tide allowing any changes to the extent and topography of the intertidal area to be appreciated. The altitude of Mean Low Water Springs is -1.85 mOD (taken from Montrose Port), and this has been compared with earlier published MLWS data.

Whilst the drone surveys were timed for low water, the full spring tidal extent was not able to be captured. Nevertheless, published Ordnance Survey MLWS are available for 2024, 2018 & 2005.

Key Results

At St Cyrus MLWS has generally advanced seawards between 2018 and 2024 at an average of +4.94 m/yr, with the greatest gain (max = +14 m/yr) at the southern end of the beach, where complexity increases with the changing orientation of the River North Esk mouth. The changes at the mouth of the North Esk and just upstream of the mouth are thought to relate to the winter 2023/24 storm season (including Storm Babet). The general pattern across the bay with increased accretional rates at the northern end (north of St Cyrus Reserve cemetery, average MLWS change rate since 2018 is +8.45 m/yr), both support the view that northerly movement of longshore drift remains dominant.

For much of the bay further south, the longer-term average rates, between 2005 and 2024, show erosion dominating much of the lower beach from Montrose Port to the northern end of Kinnaber Links (Figure 7). However, the shorter-term rates, between 2018 and 2024 show a more positive situation with the lower beach extending seawards across many areas, with the exception of two locations, including adjacent to the Golf course's 2nd hole and 7th hole. North of Kinnaber Links the lower beach shows accretion towards the mouth of the North Esk across both the latest period and more strongly since 2005. There are more complex changes around the North Esk mouth, with channels breaching through the intertidal spit, though wider changes are probably expected here due to the impacts of Storm Babet. Further north for the bulk of St Cyrus the foreshore appears to be widening with sediments gained from those erosional areas to the south.

5.1.5 Implications

The overall patterns within in Figure 7 show that over the last six years there has been many areas of accretion of MLWS, but this is superimposed on a consistent longer-term trajectory of MLWS retreat, particularly in front of Trail Drive and Montrose Links. The recent pattern of accretion seen between 2018 and 2024 is likely linked to the recent release of sediment from the rapidly eroding dunes, particularly during the period 2023-2024 where there was substantive dune retreat (as detailed in the next section). Changes to the position of MLWS since 2005 also reveal the loss of an intertidal ebb tidal spit, known as Annat Bank, in the intertidal region immediately adjacent to the South Esk channel (Figure 8). Recent research conducting hydrodynamic modelling of tidal hydrodynamics has revealed complex circulation patterns that potentially have important implications for the recirculation of sediment (Pratama and Venugopal, 2024) and further research is required to understand the interplay of regional coastal and tidal hydrodynamics with sediment transport, and implications for the broader coastal sediment budget, particularly in the vicinity of the South Esk inlet and former Annat Bank.

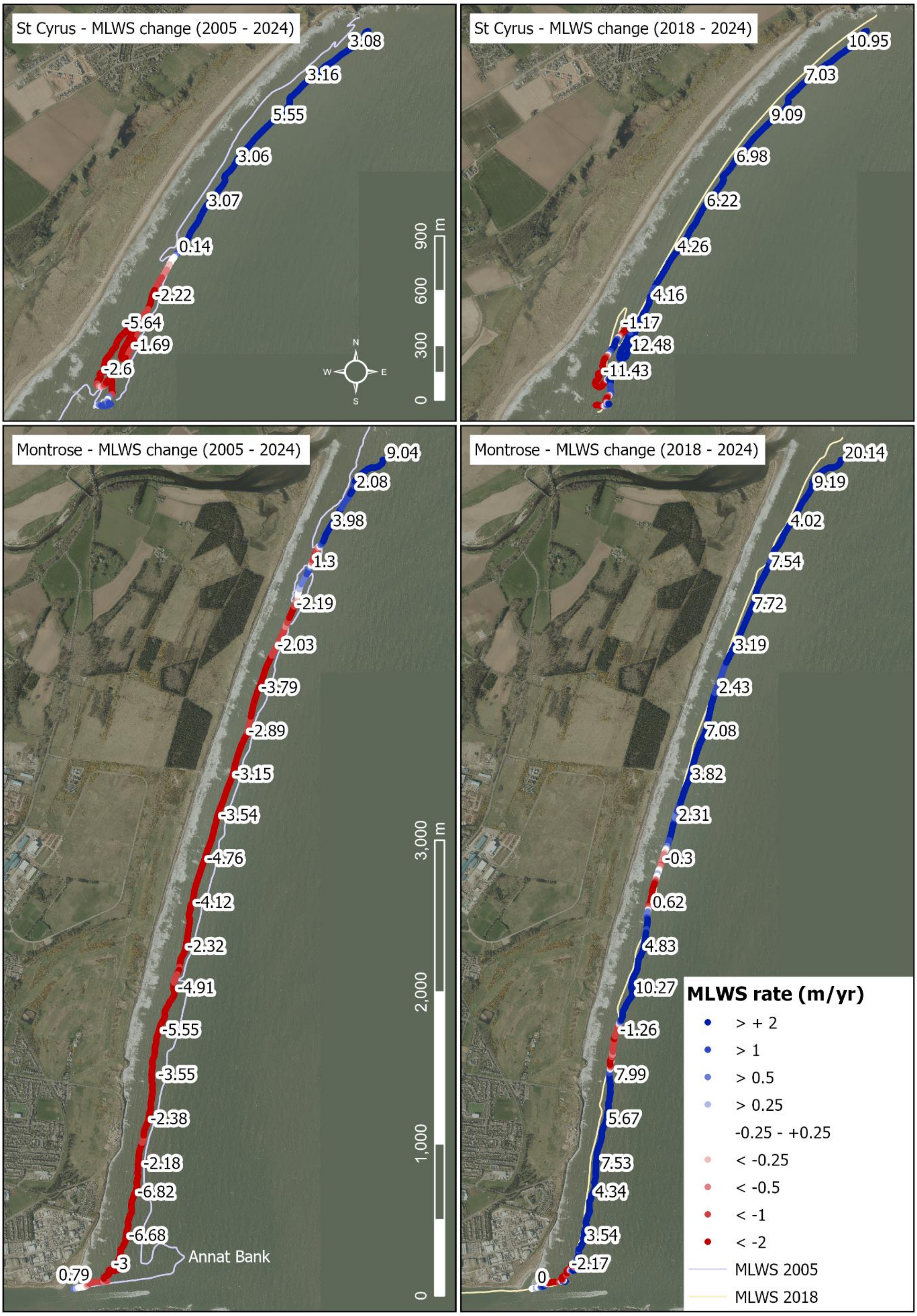


Figure 7: Changes to MLWS. Colour coded line showing MLWS position in Sept 2024, symbolised with change rate (m/yr). The left-hand panels show change over the period 2005-2024, while the right-hand panels show recent changes between 2018 and 2024 © Crown copyright and database rights 2025 Ordnance Survey (AC0000851941). © Bluesky International Ltd. & Getmapping Plc. (2025).

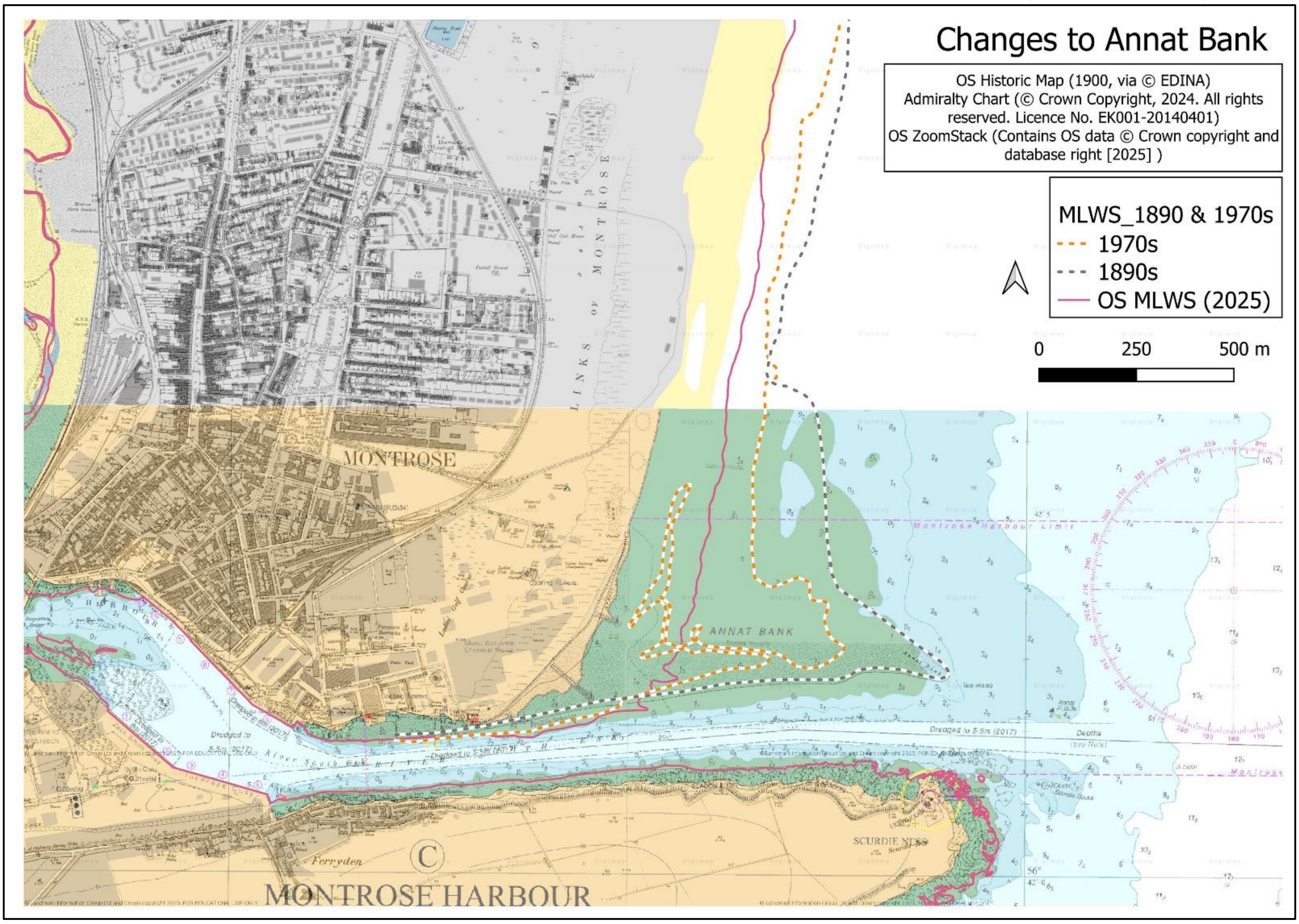


Figure 8 Map showing the historic extent of Annat Bank and how it has reduced in area since 1890s. The maintained navigation channel to Montrose Port is also shown via the coloured Admiralty Chart, though survey dates and extents are not known.

5.2 Vegetation Edge from aerial imagery

Standard methods of coastal change detection (reported in MHWS from LiDAR & topographic survey) rely on direct measurement of the beach, this is often labour intensive, and therefore costly. Whilst the methods above using MHWS and MLWS are regarded as the most traditional at identifying change, in recent times the change in vegetation edge position has become a popular indicator of coastal change too. This is pertinent at Montrose given large stretches of the bay from Traill Drive / 2nd tee north are undefended vegetated dunes.

5.2.1 Data and Methods Statement

Vegetation edge lines have been established from many of the coastal surveys at Montrose (Table 1), either by digitising aerial imagery available from a wide variety of sources, or from direct measurement during surveys (e.g. GNSS). Change in the position of vegetation edge has been accomplished by line-to-line comparison, with the more recent line having points created at regular intervals every 5m along it, and then the shortest distance to the older line being measured at each point. With the shortest distance being taken, regardless of orientation (compared to shore-normal transects used for calculating changes in MHWS), this methodology could therefore be regarded as a minimal rate of change.

The two comparative time periods chosen were September/October 2024 (UoG LiDAR) and aerial imagery from April 2011 as this gave a longer-term view over the whole of Montrose Bay, including St Cyrus. This is contrasted with a shorter comparison between the same recent LiDAR surveys and aerial imagery from April 2023 digitised to show position prior to Storm Babet (October 2023). This allows comparison of short-term changes and long-term trend.

5.2.2 Key Results

Figure 9 depicts the both the changes to the vegetation edge since 2011 and since 2023 (left and right maps respectively). The pattern is clear spatially and temporarily, in that St Cyrus shows steady dune growth which has been quickening more recently, with the exception of rapid changes at the mouth of the North Esk. Between the North and South Esk, the dune edge has been clipped back landward across the majority of the bay (with the exception of the dunes approaching both the South and North Esk rivers). Over the period 2011-2024 median rates of vegetation edge retreat are 1.13 m/yr up to a maximum of 3.86 m/yr adjacent to Montrose Links. However, rates of losses to the dune edge were much more rapid in the shorter time period 2023-2024, which coincided with the occurrence of Storm Babet, with median rates 3.37 m/yr up to a maximum of 11 m/yr.

5.2.3 Implications

The clear pattern from the dunes across the whole bay is that they are rotating clockwise, with westerly retreat in the south and easterly advances in the north. The generally quickening rate of dune retreat has been identified before, however the rates of change since the winter of 2023/24 are the fastest rates on record. This underlines the suggested disequilibrium within the bay, with the greatest changes and instability focussed to the north of the Traill Drive defences. It is unlikely that the vegetation edge will continue to separate from MHWS over the medium term, however more generally if these erosion rates within the dune edge persist then efforts to block flood corridors need to be adaptive, until the underlying instability of the beach system is addressed. This is discussed further below.

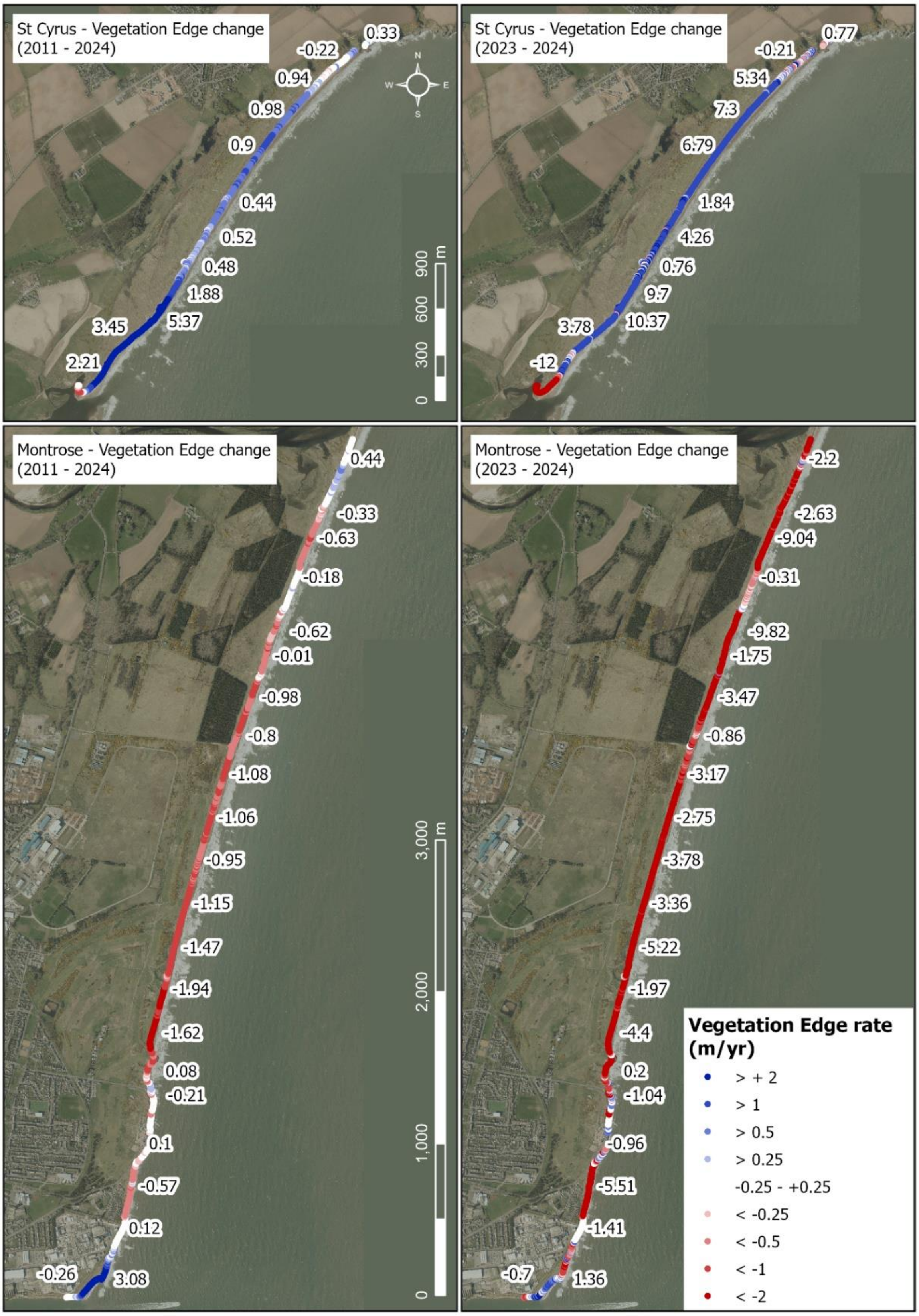


Figure 9: Map showing vegetation edge change along Montrose & St Cyrus beaches. The left-hand panels show long-term changes between 2011 and 2024, while the right-hand panel show short term changes between 2023 and 2024. © Crown copyright and database rights 2025 Ordnance Survey (AC0000851941). © Bluesky International Ltd. & Getmapping Plc. (2025).

5.3 Volumetric Change Analysis

Single metric indicators such as MHWS are useful measures for shoreline change at national and regional scales and facilitate assessment of future shoreline change. However, analysis of time series 3D datasets provides richer insights into the system behaviour and variability of volumetric changes across the entire active coastal zone (from MLWS to supra-tidal coastal vegetation). This is particularly important when considering coastal systems which provide a natural capital flood protection function to inland areas as is most certainly the case at Montrose. Volumetric change assessments also provide insights into the rates of losses of sediment that can help to inform management/adaptation actions such as beach nourishment or dune fill, and provide an important tool for monitoring of the effectiveness and health of such actions.

5.3.1 Data and Methods Statement

Whilst Dynamic Coast (2021) used rasterised Digital Elevation Models (DEMs) from 2009, 2013 & 2018, here we have compiled further datasets from more recent topographic surveys. Most of these recent surveys are derived from Unoccupied Aerial Vehicles (UAVs, also known as drones), using either photogrammetry or LiDAR methods (Goncalves & Henriques, 2015; MacDonell, et al., 2023). These surveys are most commonly focused along the golf course frontage, with some surveys having a larger extent (Table 1).

DEM datasets from different time periods can be compared, to quantify topographic changes through time by subtracting co-located pixel values to create a DEM of Difference (DoD). Using existing methodologies and Geomorphic Change Detection software (Wheaton, et al., 2010), the inherent uncertainties in the various DEMs are considered. In this instance, a probabilistic thresholding technique was used to establish change considered to be real (i.e. beyond the noise & uncertainty of the two input datasets). This technique can identify surface lowering (erosion) or surface rising (deposition). Any change identified can also be spatially aggregated to provide estimates of volumetric change, for example the volume of sediment lost or gained.

As part of the Geomorphic Change Detection software, an area with a calculated DEM of Difference (DoD), can be further segmented into smaller areas for more localised analysis of the areas and volume of erosion, accretion, and net differences (Figure 10). The major shore-parallel boundary was defined as the latest vegetation edge position (September and October 2024 for Montrose and St Cyrus respectively), with the alongshore segmentations being defined by locations / features of interest (e.g. beach access tracks, start/end of seawall or rock protections). The beach and dunes at Montrose Links have been partitioned into separate units those on the dunes have a prefix of D, those on the beach have a prefix of B, they are both numbered sequentially from north to south.

The analysis conducted looked at a series of DEMs between June 2013 and September 2024, both chronologically, but also additional DoDs for longer time periods (e.g. Jan./Apr. 2020 – September 2024). Results for Jan./Apr. 2020 – September 2024 (4.35 years) and March 2024 to September 2024 (172 days, 0.47 years) are presented below.

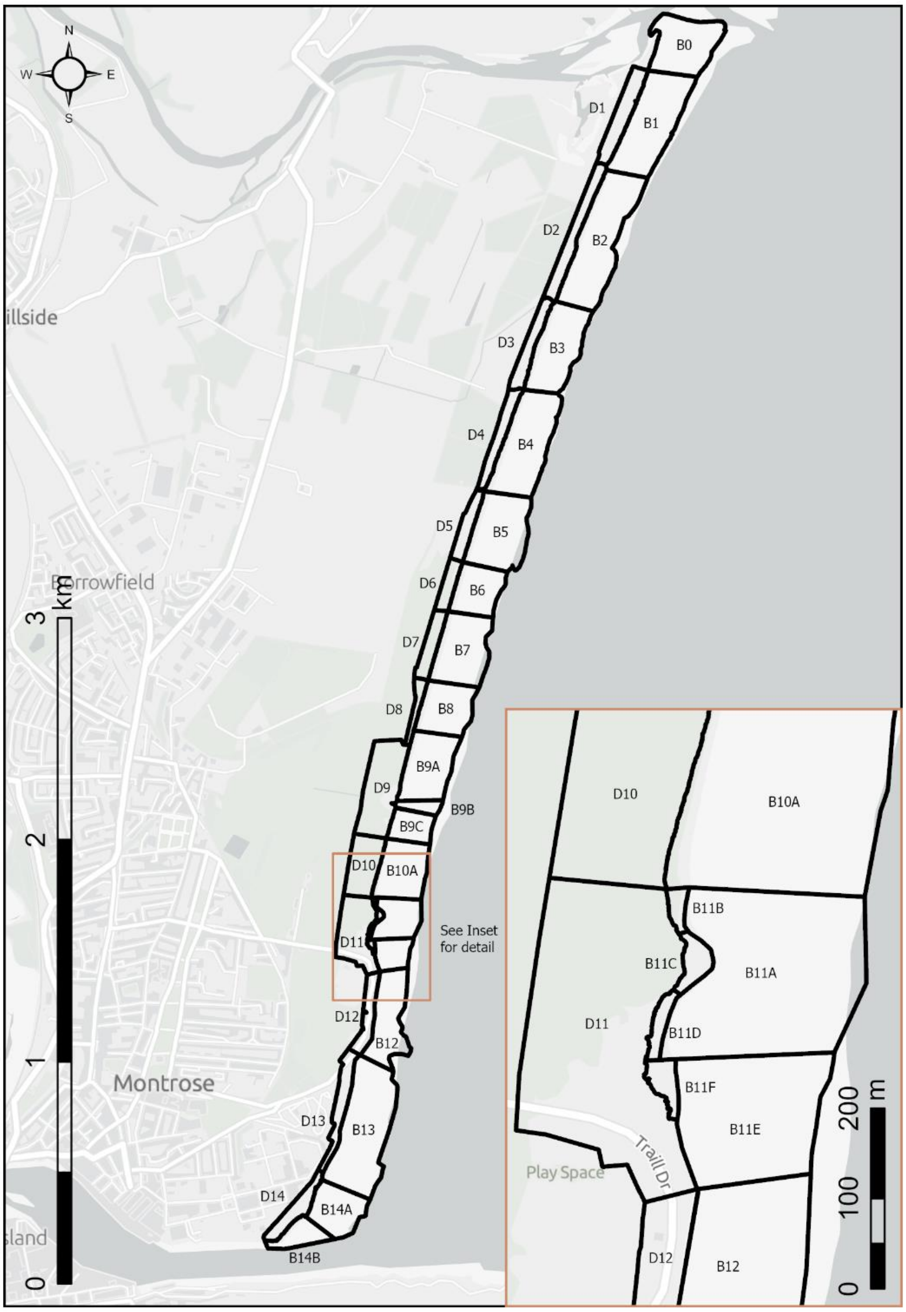


Figure 10: Geomorphic Change Detection, budget segmentation zones. Basemap: OS Light Grey via ArcGIS Pro; contains OS data © Crown Copyright and database right 2023. Contains data from OS Zoomstack.

5.3.2 Key Results

In the medium-term (2020 – 2024; Figure 11), there has been a consistent signal of dune face erosion, notably from Kinnaber Links (Zone B3 or B4) southwards to the defences at the 2nd tee (Zone B11F). There beach face is characterised by modest patches of both erosion and deposition, but with most beach zones exhibiting net sediment loss over this time period (Table 3).

In the short-term (March – September 2024; Figure 12), there has been focused dune face erosion around the second tee (Zones B11B – B11F), despite the presence of rock armouring that has been in-situ throughout this period (Zone B11C). Detailed inspection shows that the crest elevation of the defences were lowered during storm events, allowing tidal inundation over the defences. Following a liaison between Montrose Golf Links and Angus Council, the rock lowered armour has since been raised at this location, with rocks taken from defences immediately north. There is a notable patch of deposition seaward of this location, possibly deposition of material over calmer summer months or material derived directly from the adjacent dune face. There is an area of moderate lowering adjacent to the main beach access point off Traill Drive (between B11E – B11F). There is also ongoing dune face erosion to the north of this study extent in Zone B9A, to the north of the “Pipey” (Zone B9B).

Table 3: Summary of key Montrose beach sand volume changes (m^3) – medium-term (January/April 2020 – September 2024).

Area ID	Area Description	Erosion volume over 4.3yrs (m^3)	Deposition volume over 4.3yrs (m^3)	Net Volume over 4.3yrs Change (m^3)	Normalised Annual Net Volume Change rate (m^3/yr)
B1 / B2	North Kinnaber	-63,753 ± 15,800	12,180 ± 4,491	-51,573 ± 16,426	-11,856 ± 3,776
B3 – B5	South Kinnaber	-116,846 ± 16,949	52,157 ± 9,780	-64,689 ± 19,568	-14,871 ± 4,498
B6 – B9A	Golf Course to the north of "Pipey"	-106,965 ± 7,537	37,394 ± 8,015	-69,571 ± 11,002	-15,993 ± 2,529
B9A	North of "Pipey"	-29,998 ± 3,578	9,329 ± 3,889	-20,669 ± 5,285	4,751 ± 1,215
B9B	"Pipey"	-1,350 ± 474	2,193 ± 967	843 ± 1,077	194 ± 248
B9C / B10A	Golf Course south of "Pipey"	-41,764 ± 4,675	9,529 ± 3,757	-32,234 ± 5,997	-7,410 ± 248
B10A	North of 2nd Tee (2nd hole)	-31,369 ± 4,259	6,204 ± 3,407	-25,165 ± 5,454	-5,785 ± 1,254
B11B/C/D	Behind rock protection around 2nd Tee	-11,529 ± 553	116 ± 37	-11,414 ± 555	-2,624 ± 128
B12	Splash Palace seawall	-1,613 ± 956	6,253 ± 3,432	4,640 ± 3,563	1,067 ± 819
B13 – B14B	Montrose Beach South / Industrial	-36,314 ± 9,345	60,149 ± 16,560	23,834 ± 19,015	5,479 ± 4,371
Total	**All of above**	**-441,501 ± 27,116**	**195,504 ± 22,535**	**-253,683 ± 78,042**	**-58,317 ± 17,940**

Table 4: Summary of key Montrose beach sand volume changes (m^3) – short-term (March – September 2024).

Area ID	Area Description	Erosion volume (m^3)	Deposition volume (m^3)	6-month Net Volume Change (m^3)
B9A	North of "Pipey"	-3,862 ± 624	2,101 ± 1,084	-1,761 ± 1,251
B9B	"Pipey"	-24 ± 6	517 ± 269	493 ± 269
B10A	North of 2nd Tee (2nd hole)	-900 ± 246	4,836 ± 2,017	3,936 ± 2,032
B11B/C/D	Behind rock protection around 2nd Tee	-3,620 ± 282	107 ± 34	-3,513 ± 284
Total	**All of above**	**-8,406 ± 727**	**7561 ± 2306**	**-845 ± 3,836**

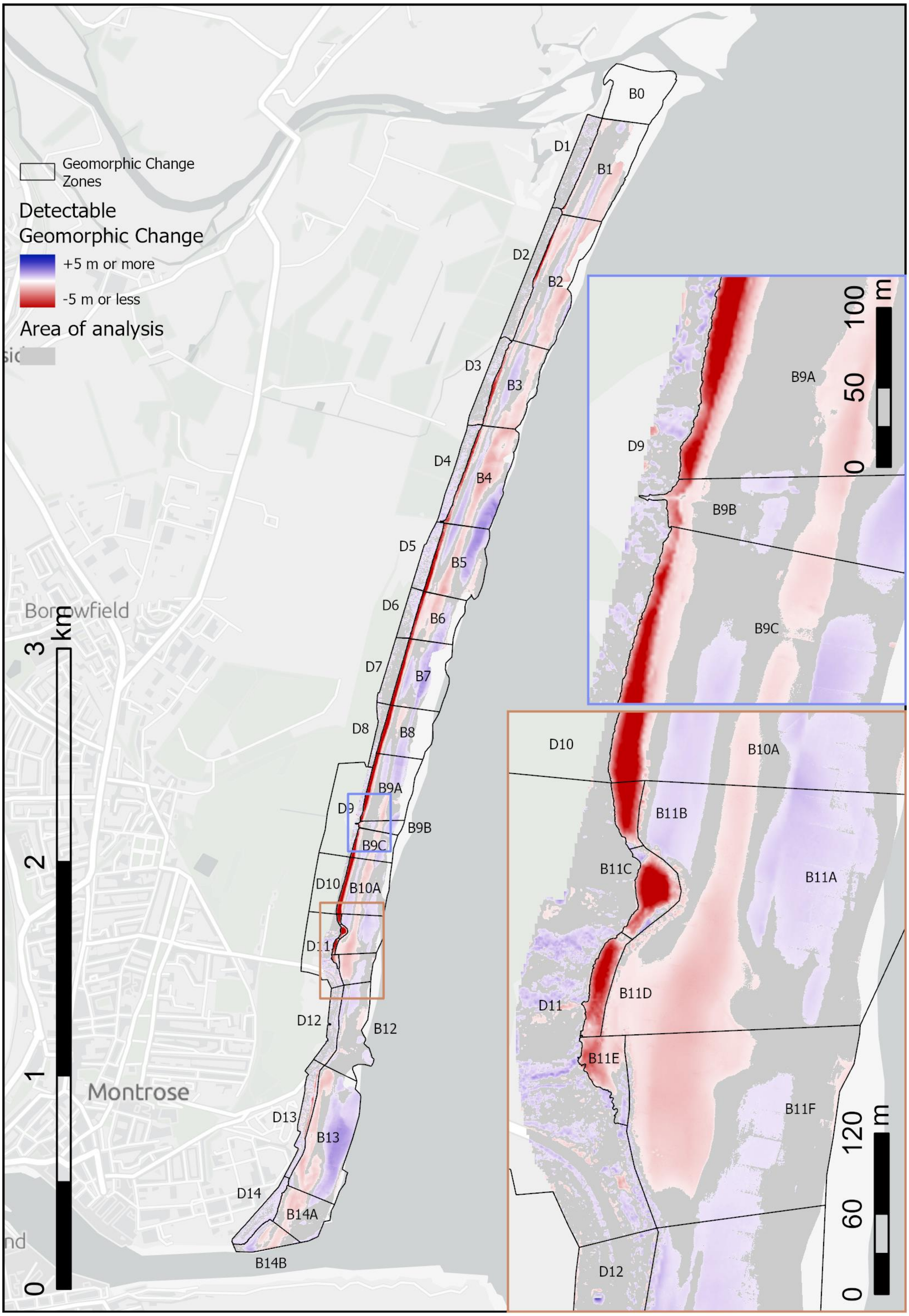


Figure 11: Medium-term Geomorphic Change Detection analysis between January/April 2020 and September 2024. Basemap: OS Light Grey via ArcGIS Pro; contains OS data © Crown Copyright and database right 2023. Contains data from OS Zoomstack.

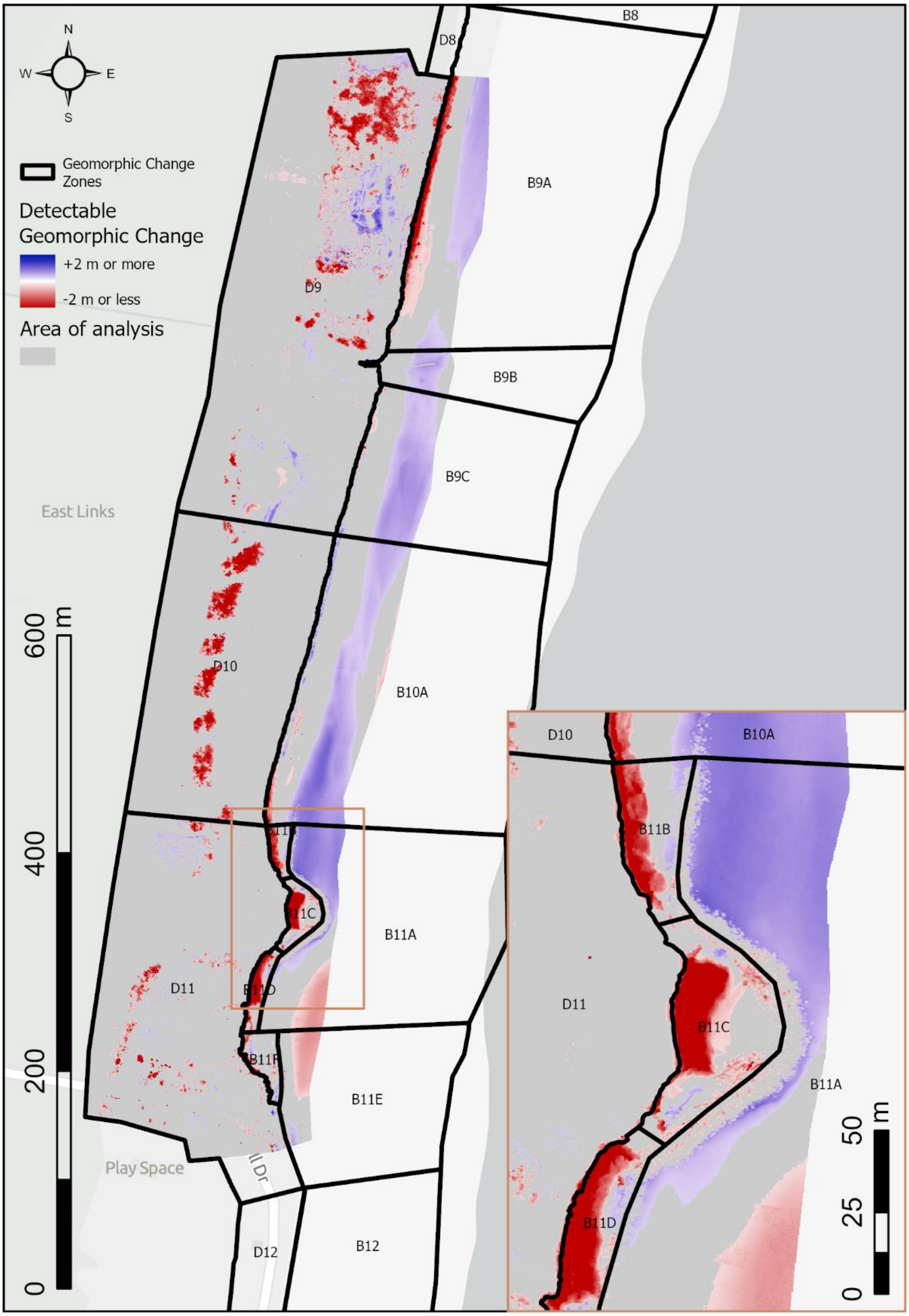


Figure 12: Short-term Geomorphic Change Detection analysis between March 2024 and September 2024. Basemap: OS Light Grey via ArcGIS Pro; contains OS data © Crown Copyright and database right 2023. Contains data from OS Zoomstack.

5.3.3 Implications

The recently commissioned survey allows volumetric changes to be identified and quantified at a local level (Figure 11 and Figure 12) however these also enable a partial sediment budget to be estimated within the surveyed areas . These show that between January/April 2020 and September 2024, approximately 58,000m3 (± 18,000) of sediment has been released/lost from the dunes and beach face between the North and South Esk rivers. Considering the area closer to the potential flood corridors, whilst over the last six months there have been losses from the dunes, much of these have fuelled gains within the adjacent areas (Table 4). The implications are that the efficacy of the flood protection feature of the dune is reducing with time, as the sediments are distributed across the foreshore and elsewhere.

Flood Corridors

The dune system at Montrose has a series of local low topography that provide the North Sea with a natural corridor with which to flood into and potentially through the natural dune barrier onto the Montrose Golf Links and potentially beyond in the future. Potential flood corridors were originally identified in the Dynamic Coast supersite report for Montrose (2021). Eight potential flood corridors have been identified and numbered from south to north (Figure 2).

5.3.4 Data and Methods Statement

In 2019, AECOM produced a study on coastal flooding at Montrose that including wave run-up calculations based on estimation methods set out in EurOtop and the CIRIA Rock Manual. The extreme water levels and their estimated return periods were estimated, however on re-inspection these were found to not be representative. AECOM have revised these calculations and the updated estimates are shown in Table 5.

Table 5: Wave Run up calculations, updated by AECOM (Many 2025) for Montrose, based on estimation methods set out in EurOtop and the CIRIA Rock Manual. The 2100 epoch runup estimations are only provided as an approximate guide. There is currently limited guidance on applying future climate change influence to wave height estimations. Runup is derived from wave height, local water depth and foreshore slope for which future conditions aren't known. The same foreshore slope and bathymetric profile is used here in both 2025 and 2100 epochs. A 10% increase in significant wave height has been applied for the 2100 epoch as a sensitivity test; from this it can be seen that sea level rise is the major part of the future increase in the tide plus runup elevation.

Return Period (years)	Water Level, WL (mAOD)	Concurrent Significant Wave Height, Hs (m) *	Mean Runup, Ru2% (m)	Tide + Runup elevation (mAOD)
2020 epoch: Mean runup estimations				
200	3.49	2.92	2.71	6.20
100	3.41	2.88	2.55	5.96
50	3.31	2.84	2.39	5.70
20	3.19	2.79	2.32	5.51
10	3.09	2.74	2.14	5.23
5	3.00	2.70	2.19	5.19
2	2.88	2.65	1.93	4.81
2100 epoch: Mean runup estimations.				
200	4.30	3.21	3.06	7.36
100	4.22	3.17	2.88	7.10
50	4.12	3.12	2.76	6.88
20	4.00	3.07	2.69	6.69
10	3.90	3.01	2.43	6.33
5	3.81	2.97	2.51	6.32
2	3.69	2.92	2.22	5.91

These new figures better align with a number of confirmed reports (from November 2020 onwards) of flooding through the dunes at the "Pipey" (Flood Corridor 6 & 7), first reported by Mr. J. Adams. More recently, Angus Council staff have also noted inundation at Profile 6. Our initial analysis of topographic levels at these locations combined with actual flooding suggests that extreme water levels have exceeded 5 mOD. Prior to AECOM's revised figures we used a nominal extreme water elevation of 5 mOD for our analysis in this report, pending further updated analysis of run-up and overtopping water levels. AECOM have revised their figures (Table 5). Separately, Dynamic Coast has commissioned separate analysis under wider coastal erosion work from JBA that estimated the annual total water level run-up (1 year Annual Exceedance Probability) at 4.2 mOD at Montrose Links (at the Pipey).

Two of these flood corridors are of particular interest given they are already subject to flooding (Flood Corridor 6 & 7), and a further corridor has also been identified as being close to a significant breach (Flood Corridor 5). Cross-section graphs have been calculated for each of the flood corridors, with elevation values extracted from a timeseries of DEMs. The maximum elevation value along each cross-section for each DEM was extracted to plot whether the corridor has been lowering and therefore providing less of a barrier to coastal flooding and storm surges (Figure 13).

5.3.5 Key Results

Our analysis has identified continued lowering of existing corridors and narrowing of the natural dunes that separates the shoreface from lower ground behind these potential corridors. Figure 13 shows the consistent lowering of the three most critical flood corridors at Montrose from June 2013 until September 2024. The graphs on the left also show how this crest location (maximum elevation value along the cross-section profile) is also migrating inland. We now have a situation where both Profile 6 & 7 are now below 5 mOD, which could be considered a regular flooding level based on observations of recent flooding. Profile 5 is not far behind either with the most recent crest elevation at 5.5 mOD.

5.3.6 Sandbag Flood Protection Structures

Angus Council secured a capital grant from the Scottish Government's Coastal Change Adaptation Fund to undertake Nature-based approaches within the dunes. As part of this they have installed three sets of shore-parallel sandbag structures whose crest elevation is 6 mOD, adjacent to these areas there has been some reprofiling of the surrounding dunes. The intention of this work was to respond to the reducing and variable flood protection offered by the dunes and provide additional short-term adaptable flood protection to the interior of the dunes, golf course and building beyond.

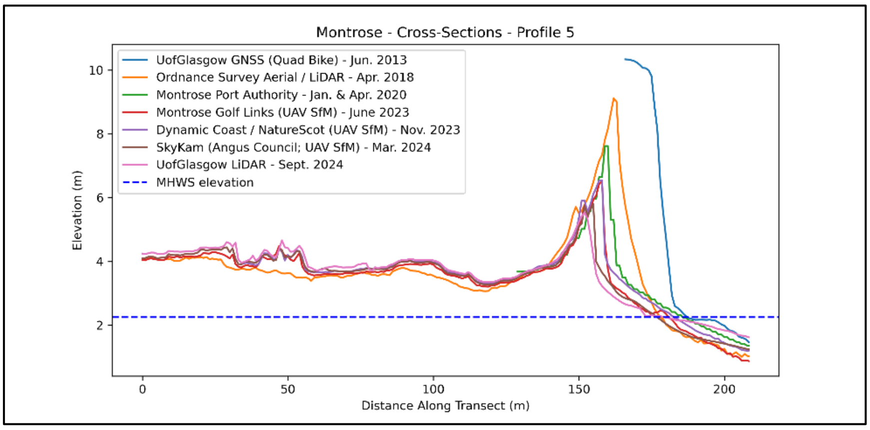
5.3.7 Implications

The sandbag structures, extending to an altitude of 6 mOD, do have a protective function against storm waves and they are adaptable structures that can be moved and rebuilt. The recent retreat rates of the dune edge can be used to inform set-back distances and estimated time periods before they are needing to be moved again. The survival period of these structures given the dune edge retreat is consider below in Task 3. An updated perspective is required for extreme water elevations and their probabilities, given that the corridor at "The Pipey" has been observed to be breached several times in recent years.

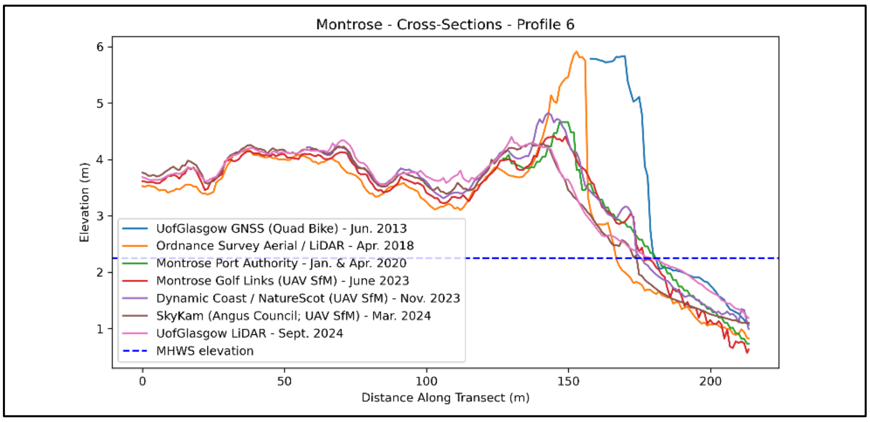
5.4 Storm response

5.4.1 Data and Methods Statement

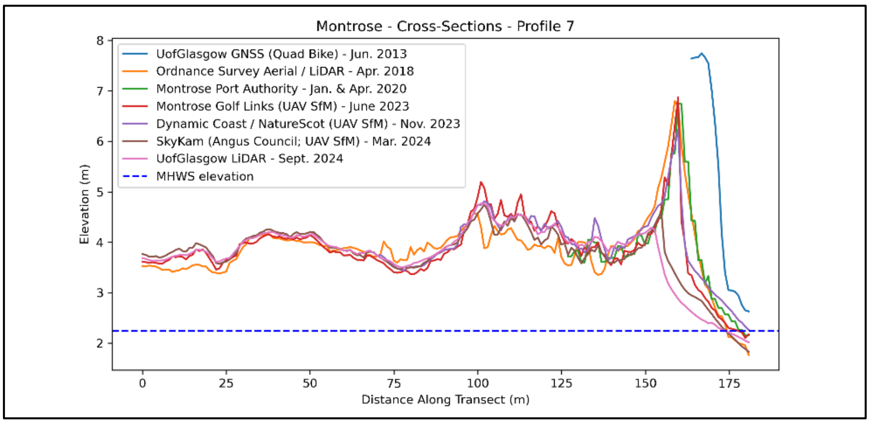
Part of the agreed works for this project was a second return survey to capture the impact of a storm event along Montrose beach (or part thereof). Although there were some storms over the 2024/2025 winter (including Storm Eowyn which coincide with neap tides), none appeared to cause significant change to Montrose beach. As such, no survey was conducted and therefore no additional analysis was undertaken to highlight the potential impact of a single storm event.



Date	Crest elevation (mOD)
Jun. 2013	10.3
Apr. 2018	9.1
Jan./Apr. 2020	7.6
June 2013	6.5
Nov. 2013	6.5
Mar. 2024	5.8
Sept. 2024	5.5



Date	Crest elevation (mOD)
Jun. 2013	5.8
Apr. 2018	5.9
Jan./Apr. 2020	4.7
June 2013	4.4
Nov. 2013	4.8
Mar. 2024	4.3
Sept. 2024	4.4



Date	Crest elevation (mOD)
Jun. 2013	7.7
Apr. 2018	6.7
Jan./Apr. 2020	6.7
June 2013	6.8
Nov. 2013	6.2
Mar. 2024	4.7
Sept. 2024	4.7

Figure 13: Cross-section profiles of Montrose Flood Corridors 5, 6 & 7, showing the evolution of the topographic elevation profiles since June 2013. Note crest elevations have been rounded to the nearest 0.1m. All three profiles now have significantly reduced maximum crest elevations, and the location of these crests are now further inland.

Figure 14: Picture showing the linear sandbag structure at the Pipey (Flood Corridor Profile 6). © J. Adams. (16th January 2025)

Figure 15a: Sandbag structure at Profile 7 (2025.03.12 c. Angus Council)

Figure 15b: Sandbag structure at Profile 5 (2025.03.12 c. Angus Council)

6 Task 3: Modelling Future Coastal Change Scenarios

Task 3 takes the observed rates of recent coastal change derived in Task 2, alongside future sea level rise scenarios (tied to global greenhouse gas emissions/shared socioeconomic pathway scenarios), to inform an assessment of the relative flood protection value offered by the dunes, under a do-nothing coastal management strategy.

6.1 Modelling future coastal change to MHWS under RCP2.6, 4.6 and 8.5 Emissions Scenarios

6.1.1 Data Statement

Future shoreline change was anticipated following the same approach used in Dynamic Coast (Hurst, et al., 2021) but informed by updated rates of historical shoreline change measured in Task 2. Historic observations of shoreline change (average rate of change in position of MHWS derived from topographic survey data via weighted regression analysis) are extrapolated forward in time using the modified Brunn Rule method (Hurst, et al., 2021), which accounts for changing sea level associated with different climate change scenarios.

Climate change scenarios are taken from the UKCP18 (Palmer, et al., 2018) projection of sea level rise for representative concentration pathway (RCP) scenarios for future greenhouse gas emissions (Figure 1). UKCP18 scenarios have now been extended out to the year 2300 and thus we are able to extend our analysis of future shoreline change out to this time horizon. However, the predictions carry a greater amount of uncertainty the further out in time they are extended (see Figure 1). We thus encourage that the focus remains on the coming decades rather than centuries. As with Dynamic Coast 2, we model a low (RCP 2.6 50%), medium (RCP 4.5 50%), and worst-case, high emissions scenario (RCP 8.5 95%). The High Emissions Scenario (RCP8.5) is used for discussion purposes, unless otherwise stated. Whilst it is not a certainty that we'll continue along this emissions pathway, it is pragmatic when considering the precautionary principle and our current trajectory. This is a concept acknowledged within Scottish Planning Policy (Scottish Government, 2023; Section 5.10), essentially where there is doubt, we should err on the side of caution. It is important to note that although the results presented below indicate a given and uncertain future, management and adaptation approaches may alter this, based on locally relevant monitoring and trigger points.

6.1.2 Key Results

Following the precautionary principle, we have here focused on the results of the RCP8.5 95th percentile scenario, as a "worst case scenario". Future predicted MHWS positions for RCP 8.5 (95%), assuming a do-nothing management strategy are shown below in Figure 16. At Montrose, this excludes what are considered temporary defence measures such as the rock boulders at the main beach access from Traill Drive and in front of the Montrose Golf Links 2nd Tee. Permanent features such as the seawall and permanent rock armour further south towards the harbour entrance (excluding the groynes) are considered by the modelling algorithm as "defences".

As detailed in Task 2, the historical rates of change used here to extrapolate into the future are slower than was the case for the 2021 Dynamic Coast 2 project (see Figure 5). The following text considers the area of beach 1km north of the ramped access point to Traill Drive (which extends to flood corridor 8). In 2021 we reported that this section of beach was eroding at an average rate of -1.50 m/yr (between 2018 & 1982), with a maximum rate of -2.4 m/yr (near flood corridor 5). However, the updated analysis here, using weighted regression reports a median rate of change to MHWS of -0.37m/yr. Whilst these rates are slower than those published in 2021, it is evident from the Table 6 below, that this still presents an issue for the dunes, and the flood protection that they provide into the future. Assuming that the horizontal offset (or gap) between the current MHWS line and the 5m contour is maintained, the inner 5m contour (which marks the landward limit of the protective part of the dunes) is expected to be compromised by between 2100 and 2150. For comparison, our earlier research published in 2021, were calibrated on earlier and more rapid rates of MHWS change (2018 vs 1982) and expected the loss of protective function to happen around 2070 or there abouts.

Table 6: Indicative breach periods of the inland 5 mOD contour (which is used as a proxy for the flood protective function of the dunes). These indicative periods include an offset between MHWS and 5m contour. Note indicative breach periods area also shown on the earlier projections published in 2021.

Area Description	Indicative breach period (updated method)	Indicative breach period (DC2 2021)
Industrial Area	2200 – 2250	Not modelled
Between 1st Hole & Traill Drive	~2250	No breach
2nd Hole	2120	~2070
3rd Hole	2090 – 2100	~2060
4th Hole (inc. Pipey)	2110 – 2120	No breach
5th / 6th Hole	2150 – 2200	~2080
7th Green (far end of golf course)	2150 – 2200	No breach
Kinnaber Links South	2150	No breach
Kinnaber Links Middle	2090 – 2100	~2080
Kinnaber Links North	2150* (North Esk impact)	~2060

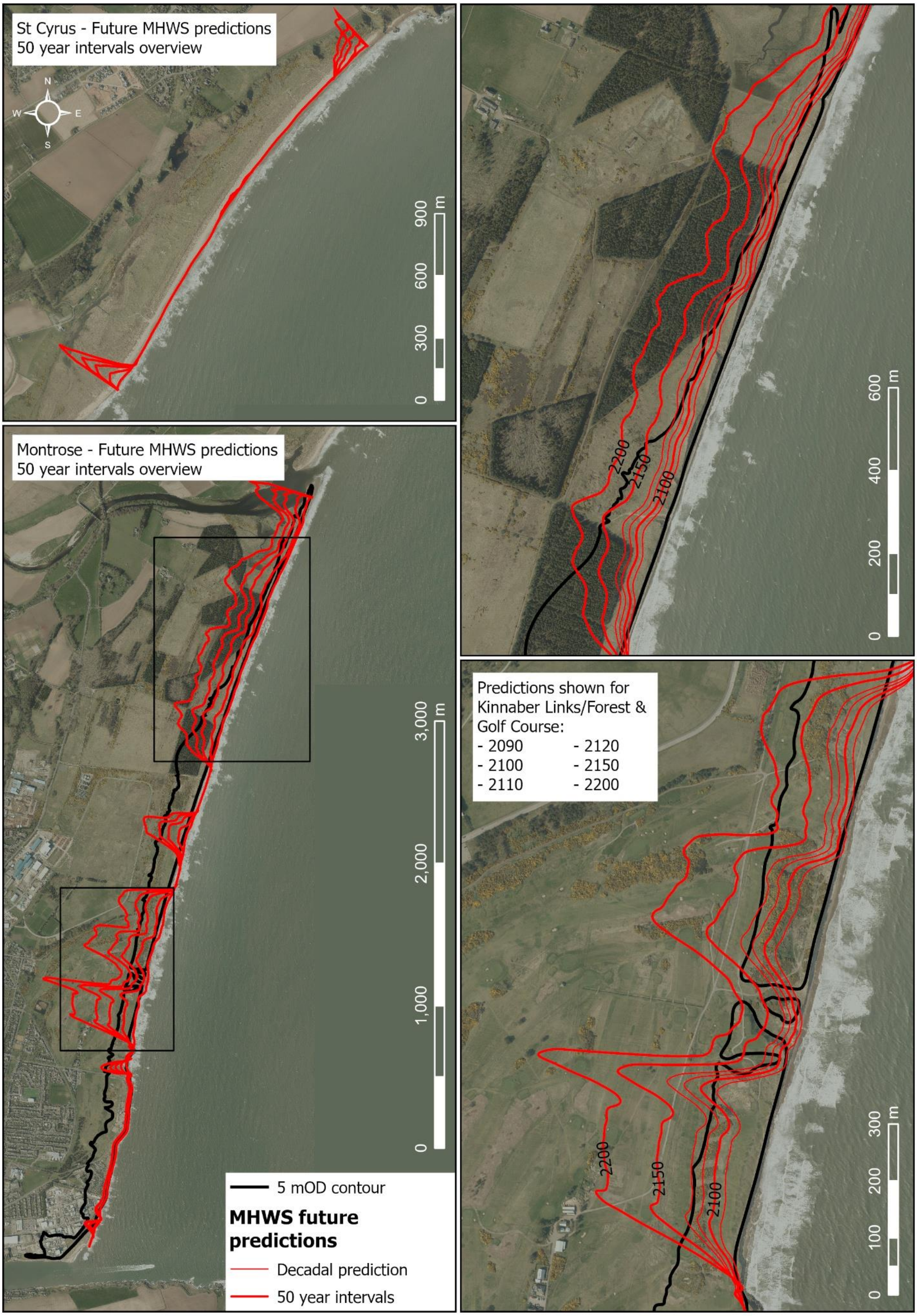


Figure 16 Anticipated future MHWS based on updated data and weighted regression method. The map shows anticipated MHWS positions for 2090, 2100, 2110, 2120, 2150 & 2200, though projections this far into the future are speculative as they are greatly influenced by calibration rates which are variable in space and time. © Bluesky International Ltd. & Getmapping Plc. (2025).

6.1.3 Implications

Based on the recent surveys and the improved methods, the implications are that continued erosion of the dunes remains a clear and present risk. Based on the updated projections, under a do-nothing management strategy and a high emissions scenario, the protective function provided by the dunes is expected to be largely compromised by ~2100 to 2150. In this situation, there may be a ~400 m gap in the high protective dunes at Montrose Links (and similar magnitude of changes are also expected at Kinnaber Links). The 5 mOD elevation has been inundated by storm waves in recent years. Of course, these estimates are based on sea levels 0.92 m higher than the present mean sea level. As a result, the current annual breaching and inundation of the dunes, by storm waves is likely to be more frequent, as are wider flood risks elsewhere on the Montrose peninsula.

Focusing on the area of the flood corridors, it is apparent that erosion rates based on MWHS have reduced more recently, in large part due to the retreat of the dune edge, and the release of sediment onto the upper beach. This amelioration in places is attributed not to the driving conditions becoming more benign (wave impacts, sediment supply or sea level for example), but due to the erosion of the dune face releasing large volumes of sediment from the dune face to be temporarily stored on the upper beach.

The implications of these reduced rates of erosion to the upper beach is a slightly slower retreat and more time expected before loss of the protective function of the dunes in places, when compared to the earlier analysis published in 2021. Assuming an offset between the MHWS line and the vegetation edge, Dynamic Coast's 2021 analysis suggested that the inner 5m contour would be breached between 2050 and 2060 for the section of beach to the north of the Traill defences. Based on the recent rates the inner 5m contour would be breached between 2100 and 2150. The recent gain in sediment on the upper beach is expected to only be temporary, and this material is expected be reworked and transported away such that retreat of MHWS will resume. The reader is encouraged to take an integrated view of the beach, not simply considering change to MHWS, but also taking cognisance of wider change to the dunes and beach as a whole. Thus, continued monitoring at a frequency that allows the observation of these fluctuations and dynamic relationships between the dune face and beach face will be important moving forward

This updated risk assessment underlines the importance of the Council's stated three stage approach: addressing short-term flood risks through the flood corridors in order to buy time, addressing the causes of the erosion (thought to be sediment supply issues within the bay, driving the erosion) within the medium-term, and therefore buys time for substantial adaptation planning beyond the coastal edge (i.e. across the Montrose peninsula). Furthermore, the importance of ongoing monitoring is clear, in that recent erosion of the dunes has fed the beach, resulting in slower rates of anticipated change, which push some of the identified risks further into the future. Of course, rates of change are fluctuating, and may also exhibit periods of more rapid erosion in future, resulting in identified risks arriving sooner. Thus, it is essential that the Council ensure they monitor ongoing coastal changes, to allow them to use this change intelligence to inform adaptation actions. This topic is considered further in Task 4, below.

6.2 Modelling future coastal change to Vegetation edge

Whilst MHWS remains the principal feature used within Dynamic Coast modelling and risk assessments, it is clear from the monitoring that the edge of the dunes (also known as Vegetation Edge) has been changing more rapidly than MHWS in recent years. The difference in rates between the dune edge and the upper beach is only expected to persist for a short period of time, whilst the build-up of sediment on the upper beach disperses. So, whilst MHWS remains the preferred feature for longer term modelling, there is merit in considering the anticipated short-term changes to the vegetation edges.

Long-term (2011-2024) and short-term (2023-2024) rates of change in vegetation edge are shown in Figure 9. Extrapolating these rates forward in time, for both the long- and short-term average rates informs the duration that the dunes can be expected to maintain their protective function (Figure 17). The more rapid rates of change associated with dune front erosion means that the dunes are expected to be breached by 2060 in the case where we extrapolate the long-term average rate of change (2011-2024) but as soon as 2030 if the rates observed in 2023-2024 were to persist.

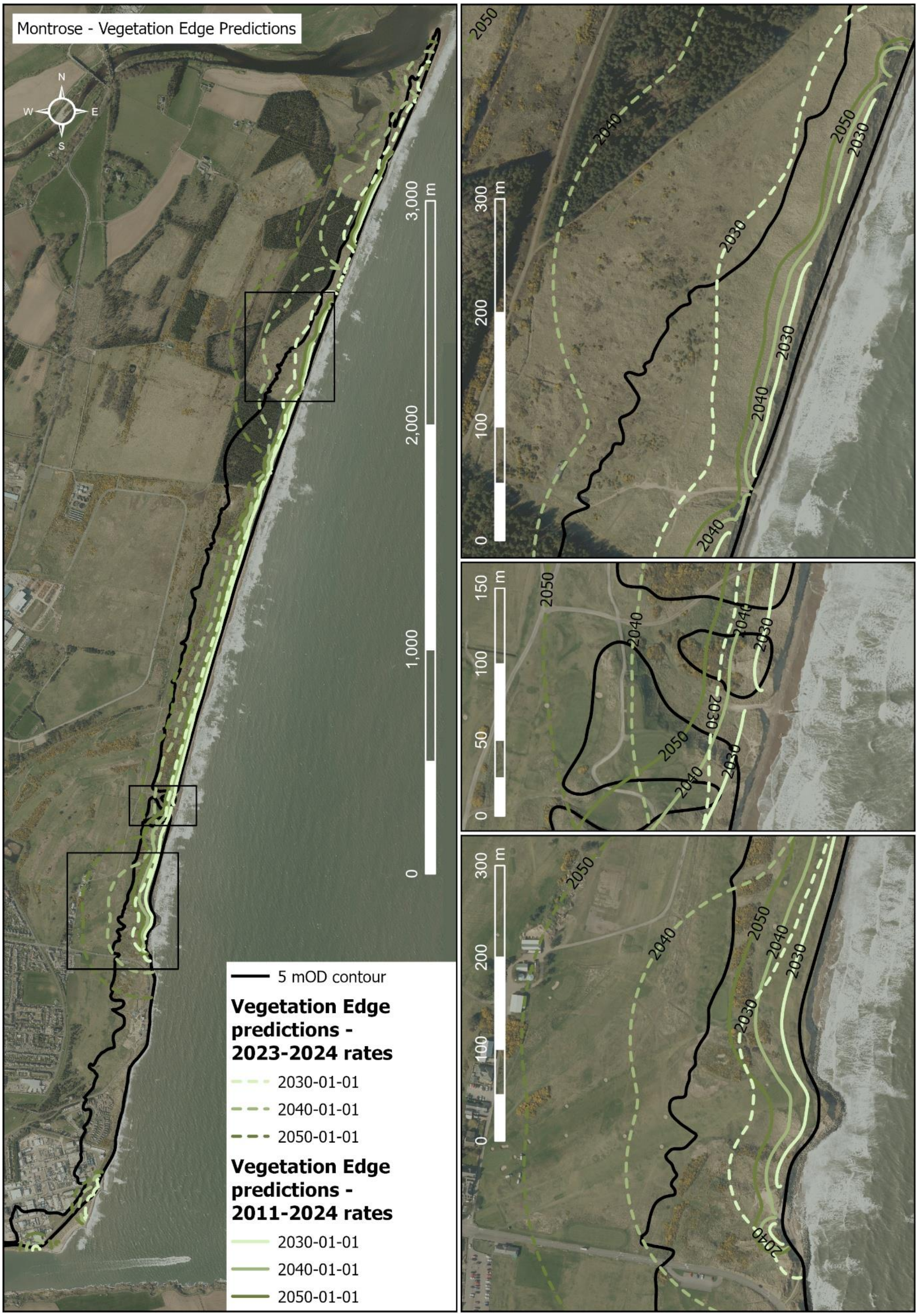


Figure 17 Maps showing anticipated future change to the dune edge (measured by vegetation edge) over a short-term and long-term period based on average rates extrapolated forward in time. © Bluesky International Ltd. & Getmapping Plc. (2025).

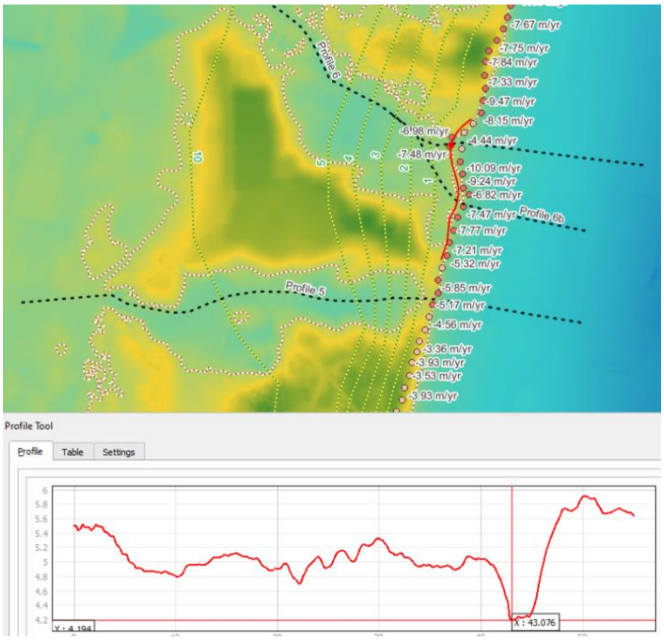
6.3 Short-term implications for the flood corridors and sand bags

The present erosion and retreat of the dune face is reducing the protective capacity provided by the dunes. Figure 13 shows the loss of high dunes and the general lowering and inland migration of the crest levels. It should be noted that during storm events, whilst much of the sediment is released and lost onto the beach face, typically a smaller amount of sediment and debris can also be carried landward into the flood corridor.

There were two further analyses undertaken to ascertain possible future changes to these flood corridors in the short-term, namely 1) cross-sectional area analysis to determine if further retreat would widen the potential flood corridor (Figure 18); and 2) assessment of the shortest distance between areas less than the flooding threshold (5 mOD) to ascertain the rate of narrowing of the barrier crest (i.e. protective function within the flood corridor) and a linear projection when a breach may occur if narrowing of the barrier crest continued (Figure 19).

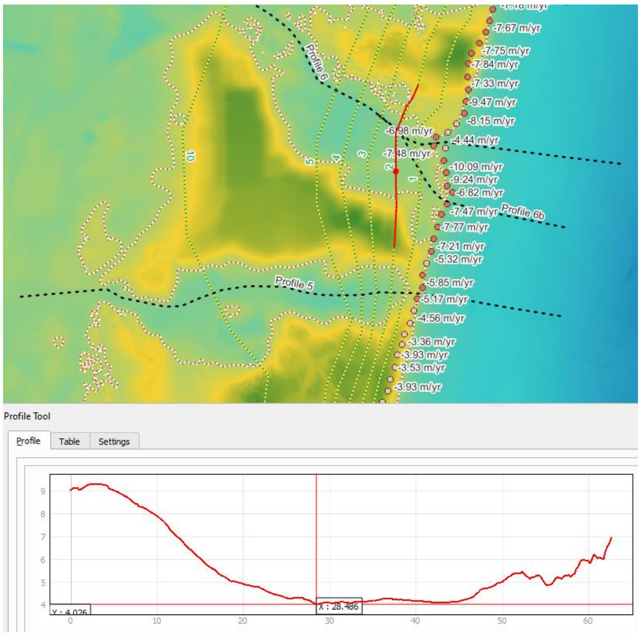
These analyses reveal that with continued erosion, the flood corridor at Pipey is expected to widen, with the potential to induce a positive feedback between inundation and erosion that could widen and deepen the corridor during wave overtopping. Flood corridor 5 is on course to be breached as soon as 2026.

Given the juxtaposition of the sandbag structures (yellow lines on the figure below) and the retreating dune edge at the flood corridors, the sandbag structure at Profile 7 is expected to be exposed on the dune face (and start to be undermined) within the first six months (based on vegetation edge retreat rates from 2023-2024). These rates appear to be validated by recent observations. Figure C shows the sandbag structure starting to appear on the dune cliff face. . For the sandbags at Profile 6 (the Pipey) parts of the wall are already seaward of the vegetated parts of the dunes; however, the entire structure is expected to be exposed within one to five years (based on one-year and five-year rates). The sandbags at Profile 5 were installed 5.5m back from the 2024.09.05 dune edge, but they are expected to be exposed between one and three years (based on the same rates as above).



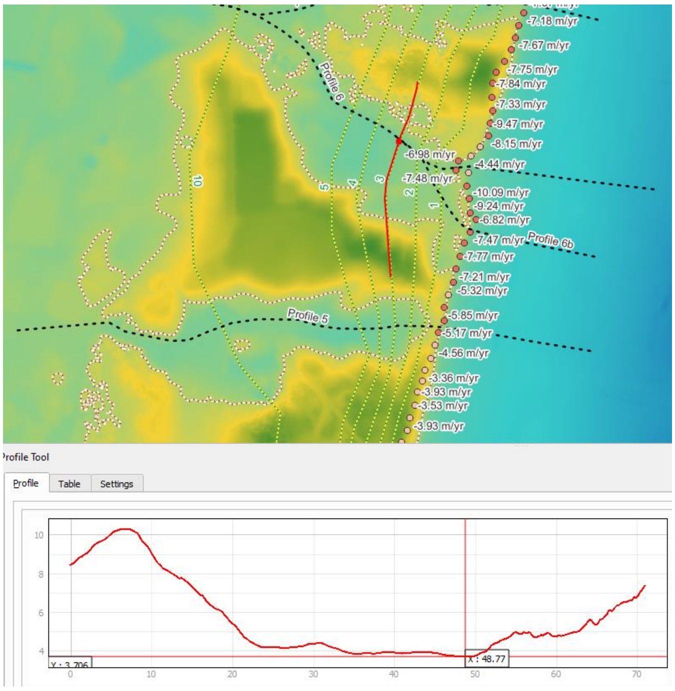
Current cross-section at dune crest.

Cross-sectional area below a nominal 5 mOD elevation is 4.35 m^2, with a minimum threshold level of 4.19 mOD.



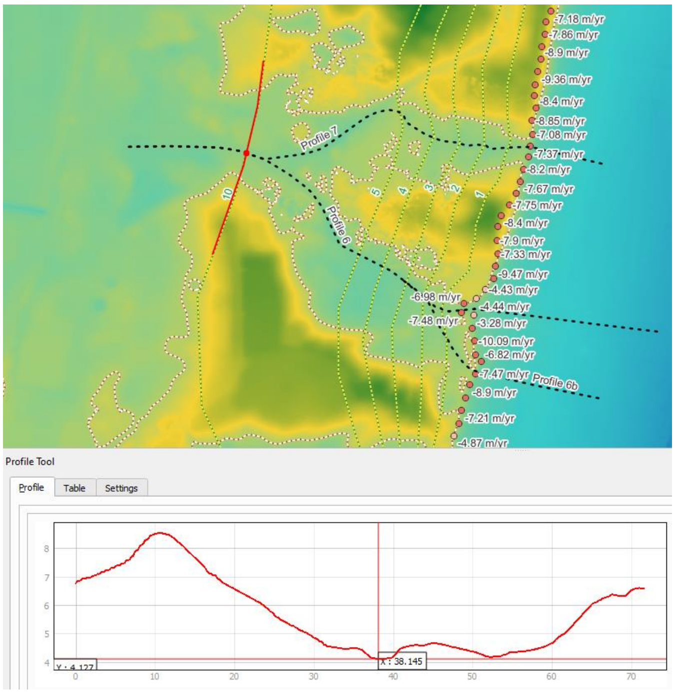
Assuming dune crest retreat at annual rate for 2 years.

Cross-sectional area below a nominal 5mOD elevation is 20.67 m^2, with a minimum threshold level of 4.03 mOD



Assuming dune crest retreat at annual rate for 3 years.

Cross-sectional area below a nominal 5mOD elevation is 29.92 m^2, with a minimum threshold level of 3.71 mOD



Assuming dune crest retreat at annual rate for 10 years.

Cross-sectional area below a nominal 5mOD elevation is 12.76 m^2, with a minimum threshold level of 4.12 mOD

Figure 18: A series of maps showing elevation models and cross sections (red line graphs) across Flood Corridor 6 at the "Pipey" to consider the changing cross-sectional area (opening or closing) of these flood corridors assuming erosion persists at the rates plotted on the points shown along the dune face.

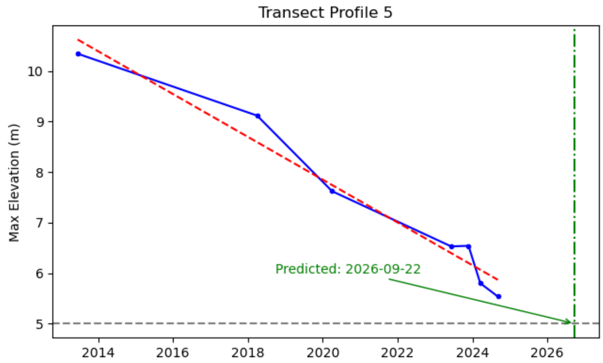


Figure 19: An example of a graph with simple linear projection of the rate of lowering of the flood corridor barrier crest, and predicting when this barrier crest will be breached. For Flood Corridor 5 (see Figure 2), this is predicted to be in mid-late 2026.

6.4 Medium-term Management Options for the flood Corridors

Angus Council aims to address the sediment deficit thought to be driving coastal change (Rennie et al 2021 & Angus Council), and therefore a medium-term option is required beyond the short-term use of sandbags to infill the flood corridors. As part of this work, the University of Glasgow were asked to identify a variety of fill volumes to raise the level of the flood corridors. The topography of each of the corridors were analysed from the most recent survey (September 2024) and various fill heights were considered (Table 7). These fill rasters were differenced to the existing topography (DEM) to establish the volume of fill required. Alongside main fill areas, tapered areas along the dune face and inland extent (using a 30° slope, Itzkin, et al., 2021) were also created and the fill volumes for these added to the final volume for each flood corridor.

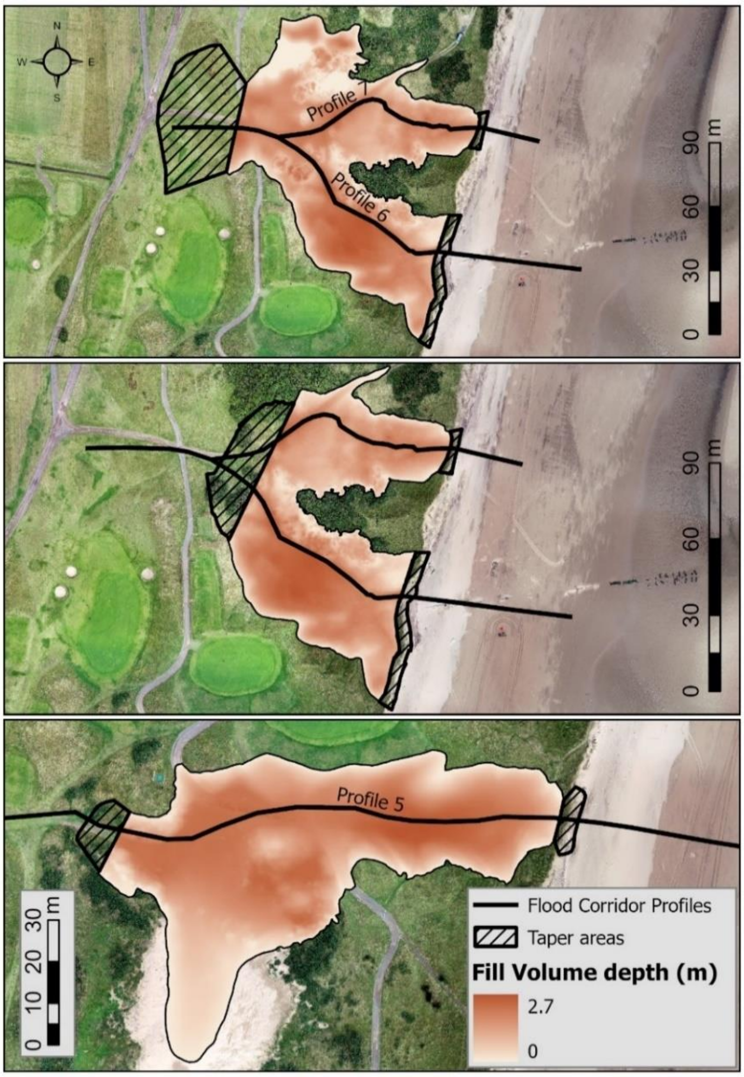


Figure 20: Fill Volume analysis for Flood Corridor profiles 5, 6 & 7 showing the depth of material required to fill these flood corridors to a 6 mOD level. Note, two variants for Flood Corridors 6 & 7 combined, with the second variant having a lesser inland extent. Further fill calculations also done for 6.5 mOD and 7 mOD (seeTable 7).

Previous analysis in this report has highlighted significant concerns about the ongoing viability of the Montrose Golf Links, particularly the 1562 course, in its current configuration. However, future management options considered, including the filling of flood corridors, need to also account for the ongoing usage and design of the golf course. Figure 20 shows the initial fill of Profile 6 & 7 (top) which extends landward over the tee shot on the 4th hole and the approach to the 16th green and similarly Profile 5 fills the run-off area short of the Par 3 3rd green. The smaller fill design for Profiles 6 & 7 (middle) would have less impact on the golf course, but consequently less protective capacity into the future. This lesser protective capacity is caveated by the fact that this scale of erosion would likely trigger other actions and would likely impact the wider course configuration anyway.

*Table 7: Fill volumes required for each Flood Corridor and given fill levels. *Total Fill Volumes use Flood Corridor 6 & 7 (Full Extent).*

	Fill Height (mOD)	Fill Volume (m^3)		Fill Height (mOD)	Fill Volume (m^3)
Flood Corridor 1	*6 m*	2,420	**Flood Corridor 5**	*6 m*	6,860
	6.5 m	3,540		*6.5 m*	9,730
	7 m	4,660		*7 m*	12,660
Flood Corridor 2	*6 m*	700	**Flood Corridors 6 & 7 (Full Extent)**	*6 m*	11,110
	6.5 m	1,010		*6.5 m*	15,530
	7 m	1,320		*7 m*	20,050
Flood Corridor 3	*6 m*	2,460	**Flood Corridors 6 & 7 (Smaller Extent)**	*6 m*	8,070
	6.5 m	3,290		*6.5 m*	11,140
	7 m	4,120		*7 m*	14,230
Flood Corridor 4	*6 m*	220	***Totals Volume (to fill all Flood Corridors to given level)****	***6 m***	***23,770***
	6.5 m	380		***6.5 m***	***33,480***
	7 m	550		***7 m***	***43,360***

7 Discussion

The surveys undertaken in September for Montrose (and October for St Cyrus) have provided important information not only informing an updated perspective of rates of coastal changes across the bay, but also revealing the complexity and variability within the coastal system. Recent rapid erosion of the dunes (i.e. vegetation edge) in response to storm activity has resulted in the release of sand causing accretion of the upper beach (i.e. MHWS). Changes to the vegetation edge of eroding dunes, such as Montrose, is related to wider beach dynamics. Vegetation edge tends to retreat landward during and following storms, which reach the foot of the dune face (also known as dune toe). Impactful storms can result in the release of sediment from the dune cliff, onto the upper beach (as has been reported here) resulting in accretion, which in turn provides some protection from storm waves coinciding with neap or low tides. For these reasons, one might expect short-term deviation between rates of change derived from vegetation edge and MHWS, but that this should not persist when averaged over extended time periods (i.e. several years integrating a number of winter storm seasons). These detailed changes observed are consistent with a beach that is experiencing a negative sediment budget punctuated by storm impacts causing release of sediment from stores (i.e. dunes) that are temporarily replenishing the shoreface until subsequent events can redistribute that sediment across and along the beach system.

This complex messaging may be unhelpful, i.e. changes to MHWS infer risks are getting less bad, but changes to vegetation edge suggests risks are getting worse. However, the coast is recognised as a complex system, and multiple indicators of change can be used to understand this complexity. Whilst a number of complementary approaches are outlined below, it may be beneficial to note that recent investigations of coastal dynamics using satellite imagery, suggests that change around the water's edge (i.e. MHWS etc) are more variable and noisier (as seen above) than changes to the vegetation edge which provide a more robust and consistent measure of change (Muir *et al*, 2024).

Figure 21 Coastal storm impacts during winter 2023/24, as reported via the Scottish Government's coastal erosion reporting tool (DynamicCoast.Com). © Crown copyright and database rights 2025 Ordnance Survey (AC0000851941).

This update provides an opportunity to remark on the recent changes but also contextualise them across Scotland. The winter of 2023/24 was particularly stormy with 12 named (and several un-named) storms, which cause considerable impacts across Scotland. 50 separate sets of storm impacts have been reported across Scotland, via the Scottish Government's Coastal Erosion Reporter (Figure 21 & DynamicCoast.com).

Reviewing these changes against the published evidence base (DynamicCoast.com) Montrose is in a unique situation (in at least Scotland), in that it is a bay-head beach that has experienced increasingly rapid erosion which has been generally persistent since at least the 1980s. Whilst erosion has affected other similar beaches they have typically experience fluctuations where rapid rates tend not to persist for decades. This appears not to be the case at Montrose. Coastal erosion is widely recognised to the controlled by changes to wave energy, sea level and/or sediment supply. Wave energy and sea level changes are not likely to be dramatically different on neighbouring beaches to that experienced at Montrose, so why has erosion persisted at Montrose?

Whilst there are many bay-head beaches with multiple rivers entering them, Montrose Port is the only river mouth port that doesn't have a breakwater adjacent to the navigation channel, isolating it from the adjacent intertidal and subtidal seabed. The possible process linkage between the beach, intertidal, subtidal and navigation channel has been investigated by Pratama and Venugopal (Pratama and Venugopal, 2024). They modelled an anti-clockwise tidal gyre (a rotational tidal current) generated by the ebb tide draining Montrose Basin as it enters the sea (Figure 22). This induced southerly currents adjacent to the southern part of the golf course and Splash area for 80% of the time. Whatever natural sediment circulation that historically existed for millennia, the routine dredging of the navigation channel, which is essential for important commercial activity, is likely to have curtailed or strongly influenced recirculation since at least 1983 (earliest dredging returns). The port is dredged under licence, to maintain safe navigation to shipping, in line with port's statutory responsibilities. The interaction of the tidal gyre and wave processes with sediment transport has not been researched as was acknowledged by Pratama & Venugopal as an opportunity for further investigation. This is something the authors of this report agree would be worthwhile.

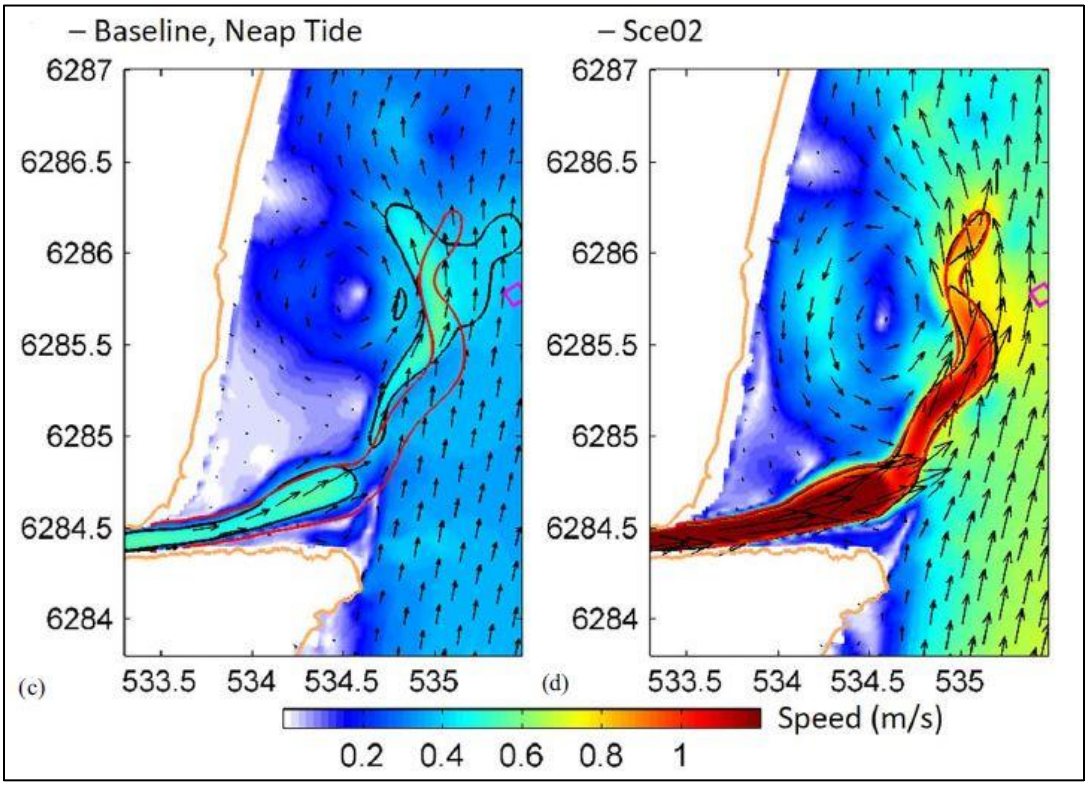


Figure 22: Depth-averaged flow pattern around inlet entrance at peak ebb phase for (c) neap tides; and (d) spring tides in Sce02, with their respective jet spline in black lines. Extract taken from Figure 12 of Pratama and Venugopal, 2024.

8 Task 4: Towards a coastal monitoring strategy for Angus Council

The coastal zone at Montrose has been observed to by highly dynamic, having undergone substantial erosion in recent years as well as being subject to a high degree of fluctuation or variability as evidenced above. Observed rates of coastal change as indicated by the changing position of Mean High Water Springs and Vegetation Edge, Mean Low Water Springs and volumetric changes (beach lowering, dune face erosion and retreat) are not always consistent with one another, and each exhibit variability in space or time. Furthermore, erosion and flood risk management / adaptation actions have already taken place and are expected to be further adapted in the short-term. Taken together, these factors motivate the need for a coastal monitoring strategy that can capture changes across the range of time and space scales at which significant changes occur, and also allow for assessment of the effectiveness and lifespan of any active or planned management / adaptation interventions.

Options for coastal monitoring approaches span a range of time and space scales and resolutions, with associated trade-offs in terms of costs. Here we outline recommended monitoring approaches that can best integrate across the range of appropriate time and space scales.

8.1.1 Coastal UAV Surveys

The survey approach undertaken in September/October 2024 for this report involved the use of unoccupied aerial vehicles (UAV or drones) to conduct a high spatial resolution (<10cm) photographic and LiDAR topographic survey of the Montrose and St. Cyrus foreshore and hinterland. This approach allows for mapping of key coastal indicators (MHWS, Vegetation Edge) but also facilitates the more detailed perspective that 3D volumetric change analysis can provide. Volumetric analysis is vital for providing estimates of the volumes of sediment that may be lost or gained over a period of time and therefore can inform calculations of volumes needed for fill/nourishment if being considered as an adaptation option. Volumetric analysis will also allow for detailed assessment of the effectiveness of current or future adaptation actions. We recommend at minimum annual surveys, but biannual is better since it informs assessment of seasonality (via pre and post-winter surveys). It would also be prudent to be agile for completion of post-storm response surveys as and when the Montrose coast is impacted.

8.1.2 Satellite-derived coastal change indicators

The position of Mean High Water Springs (MHWS) has previously been used as a principal coastal change indicator by Dynamic Coast (Hurst, et al., 2021), however these analyses were based on sparse observations and few available topographic surveys. Recent developments in the deployment of software to automate analysis of satellite imagery allows for a richer time series of shoreline observations to be generated, albeit at coarser resolution with larger uncertainties than ground surveys and observations. We have been testing the deployment of the CoastSat software (Vos, et al., 2019) to extract time series of water edges for satellite images that coincide with high tide elevations and can be tidally corrected for beach slope (measured from a LiDAR topographic survey) to correct to an equivalent MHWS elevation. Satellite observations can be made at a frequency as low as once every 15-30 days (frequency is dependent on requiring cloud-free conditions). Furthermore, researchers at UofG have developed novel approaches to automate the mapping of vegetation edges from satellite observations (Muir et al., 2024). The seaward edge of terrestrial vegetation marks what is commonly perceived to be the coastal edge, any movement of which is usually interpreted as coastal erosion. and derive average rates of shoreline change by regression analysis of shoreline position through time. Therefore monitoring of vegetation edge and mean high water springs via satellite observations has the potential not only to provide a near-continuous and ongoing monitoring service, albeit at coarse spatial resolution, but also to enrich the back-catalogue of shoreline observations to build further confidence in findings of this report.

8.1.3 Regional and National data capture

Whilst local authorities have statutory responsibilities that mean that they have an interest in commissioning and capturing their own data (as above) there are routine surveys being undertaken by other organisations. These include the repeated aerial surveys available under the Public Sector Geospatial Agreement (imagery and associated height data provided by APGB BlueSky), and alongside this there are periodic LiDAR surveys commissioned by the Scottish Government (link to portal). Scottish Government is undertaking Land and Coastal LiDAR in 2025/26 which may also provide valuable data. These may provide ad-hoc data which can also inform the programmed work above.

9 References

Bruun, P., 1954. *Coast erosion and the development of beach profiles,* s.l.: US Beach Erosion Board.

Burgess, K. & CH2M, 2020. *Impact of climate change on asset deterioration,* Bristol: Environment Agency.

Department for Environment, Food and Rural Affairs, 2006. *Shoreline management plan guidance; Volume 1: Aims and requirements & Volume 2: Procedures,* London: Department for Environment, Food and Rural Affairs.

East Lothian Council, 2002. *East Lothian Council Shoreline Management Plan Final Report,* Glasgow: Babtie Group, ABP Research & Consultancy Ltd.

Environment Agency, 2020. *Impact of climate change on asset deterioration (Report - SC120005/R1),* Bristol: Environment Agency.

Fitton, J., Rennie, A., Hansom, J. & Muir, F., 2021. Remotely sensed mapping of the intertidal zone: A Sentinel-2 and Google Earth Engine methodology. *Remote Sensing Applications: Society and Environment,* Volume 22, p. 100499.

Goncalves, J. & Henriques, R., 2015. UAV photogrammetry for topographic monitoring of coastal areas. *ISPRS Journal of Photogrammetry and Remote Sensing,* Volume 104, pp. 101-111.

Hurst, M., Muir, F., Rennie, A. & Hansom, J., 2021. *Dynamic Coast: Future Coastal Erosion,* s.l.: Scotland's Centre of Expertise for Water (CREW).

IPCC, 2021. *The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,* Cambridge: Cambridge University Press.

IPCC, 2022. *Climate Change 2022: Impacts, Adaptation, and Vulnerability, 2022. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,* Cambridge: Cambridge University Press.

Itzkin, M. et al., 2021. The relative influence of dune aspect ratio and beach width on dune erosion as a function of storm duration and surge level. *Earth Surface Dynamics,* 9(5), pp. 1223-1237.

MacDonell, C. J. et al., 2023. Consumer-grade UAV solid-state LiDAR accurately quantifies topography in a vegetated fluvial environment. *Earth Surface Processes and Landforms,* 48(11), pp. 2211-2229.

Met Office, 2019. *UKCP18 Science Overview Executive Summary,* Exeter: Met Office.

Muir, F., Hurst, M., Rennie, A. & Hansom, J., 2021. *Dynamic Coast: National Coastal Erosion Risk Assessment,* s.l.: Scotland's Centre of Expertise for Waters (CREW).

Muir, F. et al., 2023. *Watching the Grass Grow: Delineating Coastal Vegetation Edges from Satellite Imagery.* Edinburgh, British Society of Geomorphology.

Naylor, L., 2023. *Annex 5 – Technical Annex: The West African Coastal Barrier System Coastal Erosion, Flooding, Climate Change Adaptation, and Resilience.,* s.l.: The World Bank Inspection Panel.

Palmer, M. et al., 2018. *UKCP18 Marine Report,* Edinburgh: Marine Scotland.

Pratama, M. & Venugopal, V., 2024. Modeling Tidal Hydrodynamics of the Montrose Tidal Inlet System: Ebb Jet and Eddy Formation at a Tidal Inlet with a High-Angle Half-Delta. J. Waterway, Port, Coastal, Ocean Eng., 2024, 150(6): 04024016

Price, C. & Baxter, J., 2021. *Presentation to Fisherrow consultation area.* Musselburgh: Musselburgh Flood Protection.

Rennie, A. et al., 2021. *Dynamic Coast: The National Overview (2021),* s.l.: Scotland's Centre of Expertise for Water (CREW).

Rosati, J., Dean, R. & Walton, T., 2013. The modified Bruun Rule extended for landward transport.. *Marine Geology,* Volume 340, pp. 71-81.

Schwalm, C., Glendon, S. & Duffy, P., 2020. RCP8.5 tracks cumulative CO2 emissions. *Proceeding of the National Academy of Sciences,* 117(33), pp. 19656-19657.

Scottish Government, Committee on Climate Change, 2022. *Is Scotland climate ready?,* Edinburgh: Scottish Government.

Scottish Government, 2023. *Coastal Change Adaptation Plan Guidance (Interim Guidance),* Edinburgh: Scottish Government.

Scottish Government, 2023. *Scotland's Guiding Principles on the Environment: Statutory Guidance. Prepared under section 17 of the UK Withdrawal from the European Union (Continuity) (Scotland) Act 2021,* Edinburgh: Scottish Government.

Vos, K. et al., 2019. CoastSat: A Google Earth Engine-enabled Python toolkit to extract shorelines from publicly available satellite imagery. *Environmental Modelling and Software,* Volume 122, p. 104528.

Vousdoukas, M. et al., 2020. Sandy coastlines under threat of erosion. *Nature climate change,* 10(3), pp. 260-263.

Wheaton, J., Brasington, J., Darby, S. & Sear, D., 2010. Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets.. *Earth Surface Processes and Landforms,* 35(2), pp. 136-156.

10 Glossary

3D: Three dimensional; in the context of this report, usually referring to the addition of vertical data (e.g. elevation models) for analysis

Accretion: the build-up of coastal sediment typically by wave, tide, or wind processes, which leads to the seaward movement of contours such as MHWS lines

Beach nourishment: the artificial addition of appropriate sediment to a beach to ameliorate coastal erosion.

CCC: The UK Committee on Climate Change, which provides independent review to UK Governments

CCAF: the Scottish Government's Coastal Change Adaptation Fund. See www.DynamicCoast.com/cca

CCAP: Coastal Change Adaptation Plans, these are new plans which replace SMPs (see below)

DEM/DSM: Digital Elevation Model (or Digital Surface Model), a regular gridded image raster with each cell containing a height for the given location

Earth Observation: refers to the use of remote sensing technologies to monitor land, marine (seas, rivers, lakes) and atmosphere. Satellite-based EO relies on the use of satellite-mounted sensors to gather data about the Earth's characteristics. The images are then processed and analysed in order to extract different types of information that can serve a very wide range of applications and industries.

Erosion: the removal of coastal sediment typically by wave, tide, or wind processes, which leads to the landward movement of contours such as MHWS lines.

Groyne: an artificial structure which acts as a barrier to sediment moving along the coast

LiDAR: Light Detection And Ranging; a laser scanning device for accurate measurement of heights & distances.

Macrotidal: areas where the tidal range is greater than 4 m

MU1: Management Unit 1, an area defined within a SMP

MHWS: Mean High Water Springs, the upper coastal line used to define the beach

MLWS: Mean Low Water Springs, the lower coastal line used to define the beach

Precautionary Principle: where there is uncertainty a precautionary approach should be undertaken

Raster: a pixel-based spatial dataset, for example an image or Digital Elevation Model

RCP: Representative Concentration Pathways including 2.6 (often referred to as a Low Emissions Scenario, in line with the Paris Agreement, 4.5 (Medium Emissions Scenario) and 8.5 (High Emissions Scenario).

RCP8.5 95%: the percentage figure refers to the 95th percentile of a range of projected sea levels

SMP: Shoreline Management Plan

OD: Ordnance Datum; standard height datum used in Great Britain for the measurement of mean sea level as defined by the Ordnance Survey using a tide gauge at Newlyn.

OS: Ordnance Survey; the national mapping agency for Great Britain.

Transect: a line extending perpendicular to the shoreline, which measurements are made along

UAV: Unoccupied Aerial Vehicle, colloquially known as a Drone

UoG: University of Glasgow

VE: Vegetation Edge, the edge of terrestrial vegetation adjacent to beach sediments often used for coastal change assessments